My research

http://splox.net

- Exoplanet detection and characterisation
  - mostly transits (CoRoT, Kepler, K2, TESS, PLATO, HST, ground-based spectroscopy)
  - also working on RV and astrometry
- Stellar activity
  - as a noise source for exoplanet studies
  - in its own right: stellar rotation and activity from transit surveys
- Statistical methods
  - Analysis of time-series data with correlated noise (Gaussian Processes)
  - Bayesian model comparison and parameter estimation

Oxford Astrophysics

www2.physics.ox.ac.uk/research/astrophysics

- 130 faculty, postdocs & PhD students
  - within largest physics dept. in UK
- Cosmology
  - CMB, large scale structure, weak lensing, modified gravity
- Galaxies & black holes
  - galaxy surveys, active galaxies, galactic dynamics and stellar populations, accretion and jet physics, gas in galaxies
- Stars and exoplanets
  - observations, formation and dynamics of planetary systems, stellar structure and evolution, pulsars and compact objects, astrophysical fluids
- Instrumentation
  - high energy, visible and near-IR, mm wavelength detectors, experimental radio cosmology
- Large projects
  - SKA, E-ELT, Euclid, JWST, LSST, CTA, PLATO, SDSS-4….

Stellar activity and exoplanets: synergies and challenges

Suzanne Aigrain

Vinesh Rajpaul, Ruth Angus (Oxford Astrophysics)
Steve Roberts, Mike Osborne (Oxford Engineering Science)
Neale Gibson (ESO), Amy McQuillan (Tel Aviv)
Frederic Pont (Exeter), Shay Zucker, Tsevi Mazeh (Tel Aviv)

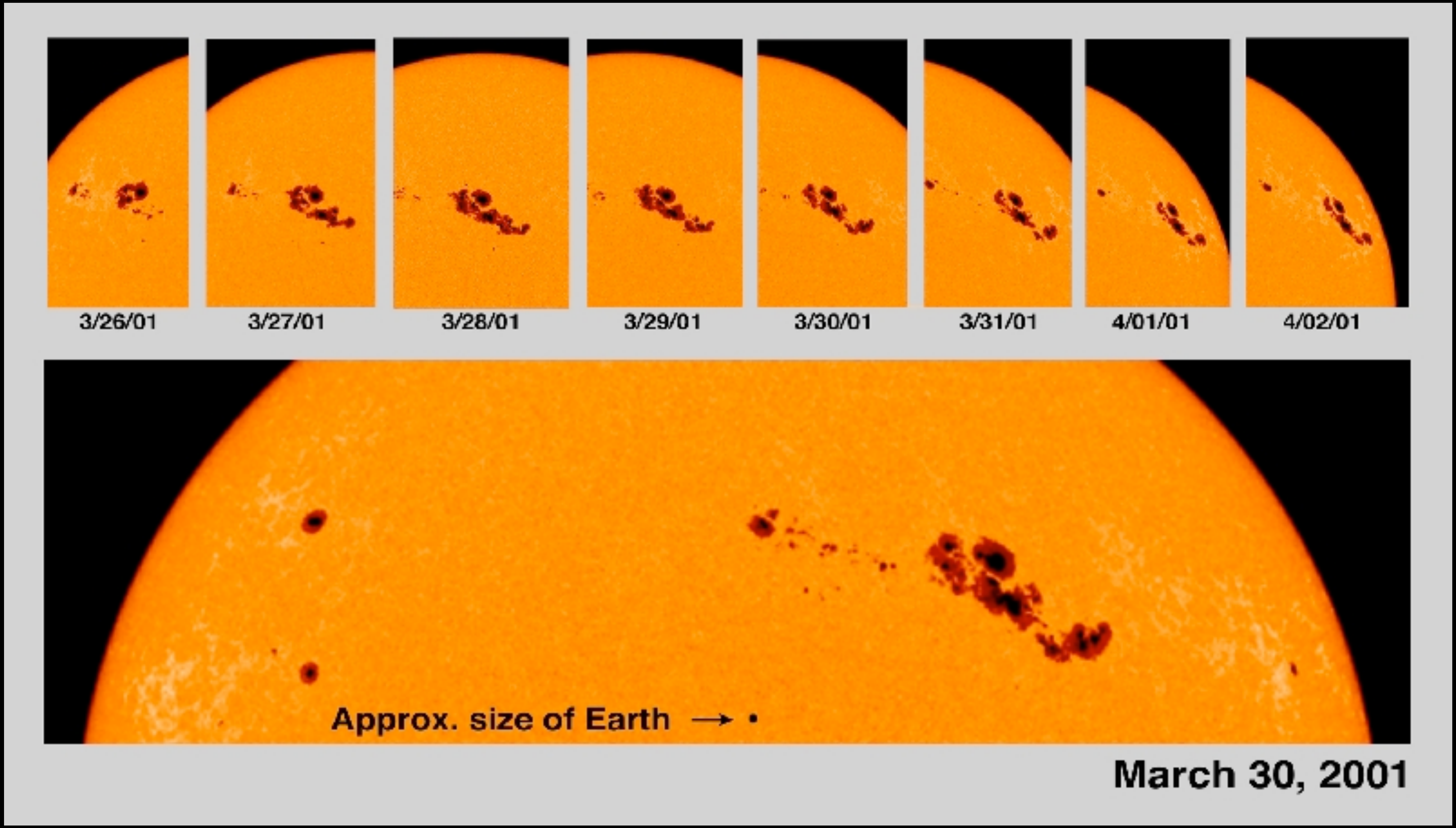
UNIVERSITY OF OXFORD

Outline

- **Activity as the noise**
  - transit detection
  - transmission spectroscopy
  - **radial velocities**
- **Activity as the signal**
  - rotation studies from transit surveys
  - spot spectra from transits
  - spot mapping and differential rotation from transits
- **Searching for planets around young stars with K2**

Photometric effects of spots

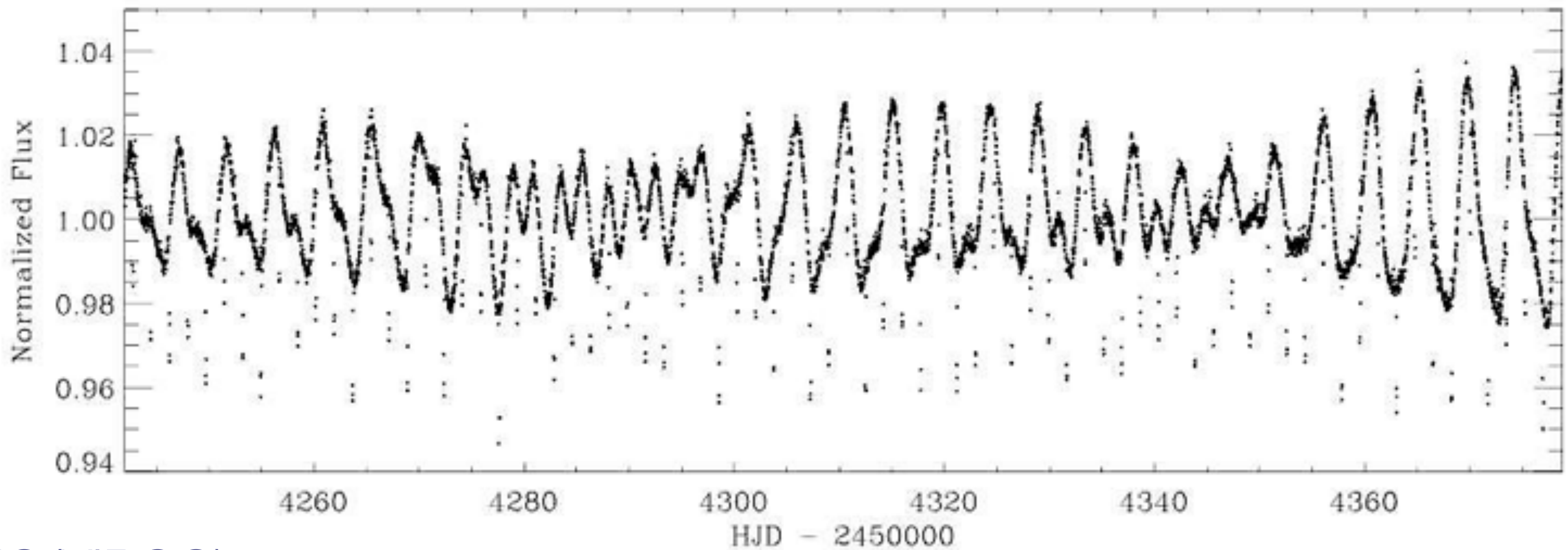
SoHO/MDI continuum intensity



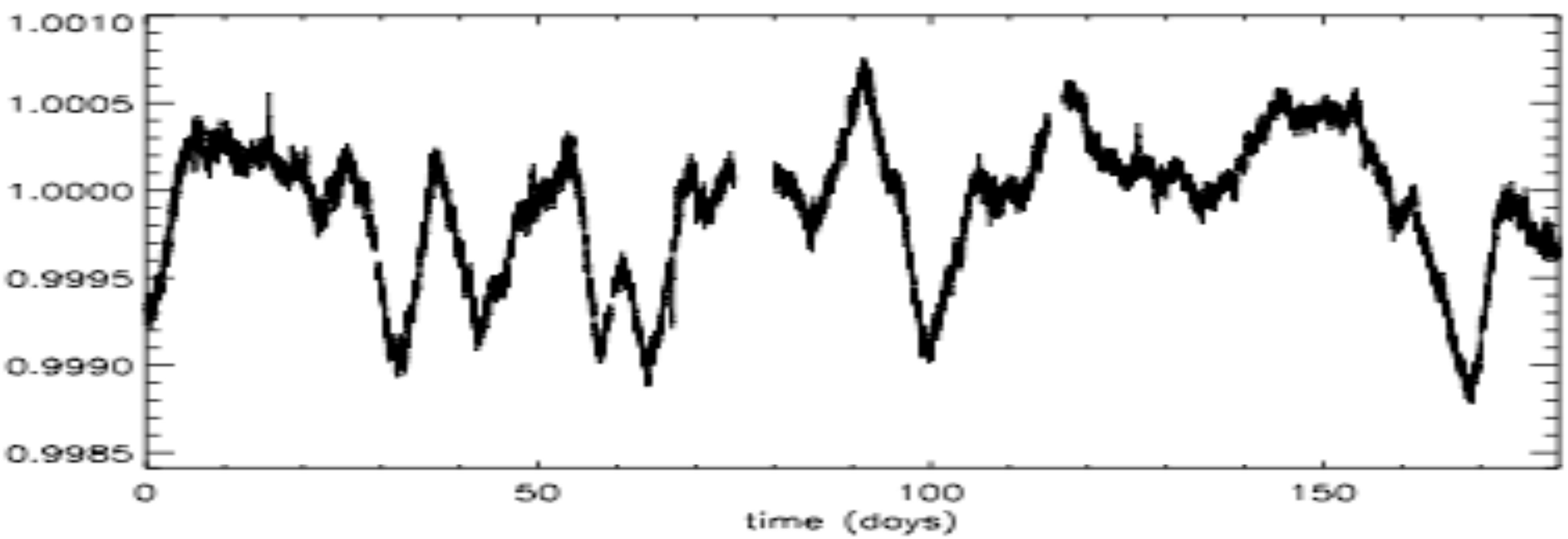
Note faculae (limb-brightened, low contrast) and granules (minimal effect over whole disk)

Photometric effects of spots

Active star (CoRoT-2)

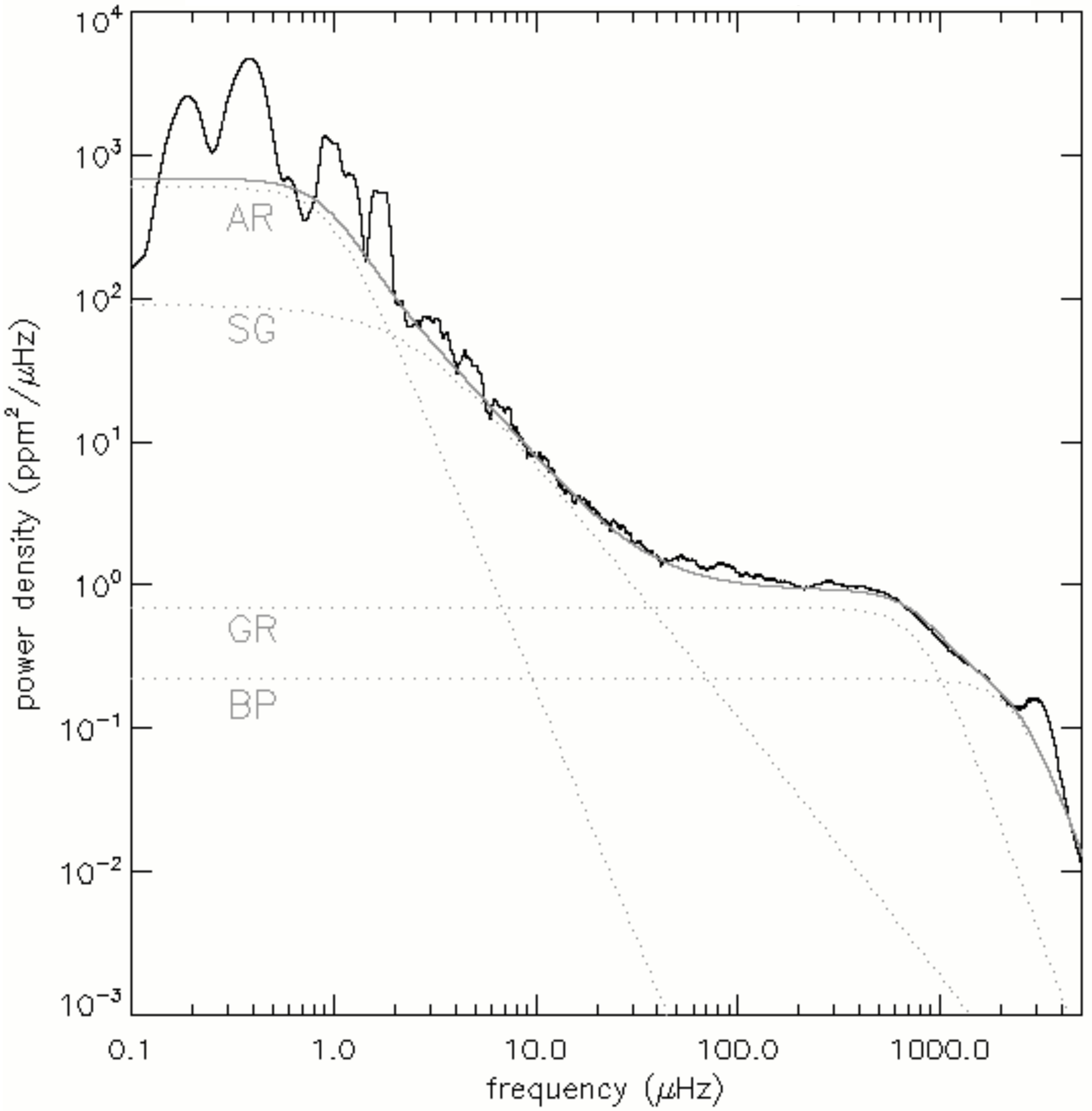


Sun (SoHO/VIRGO)



Timescales

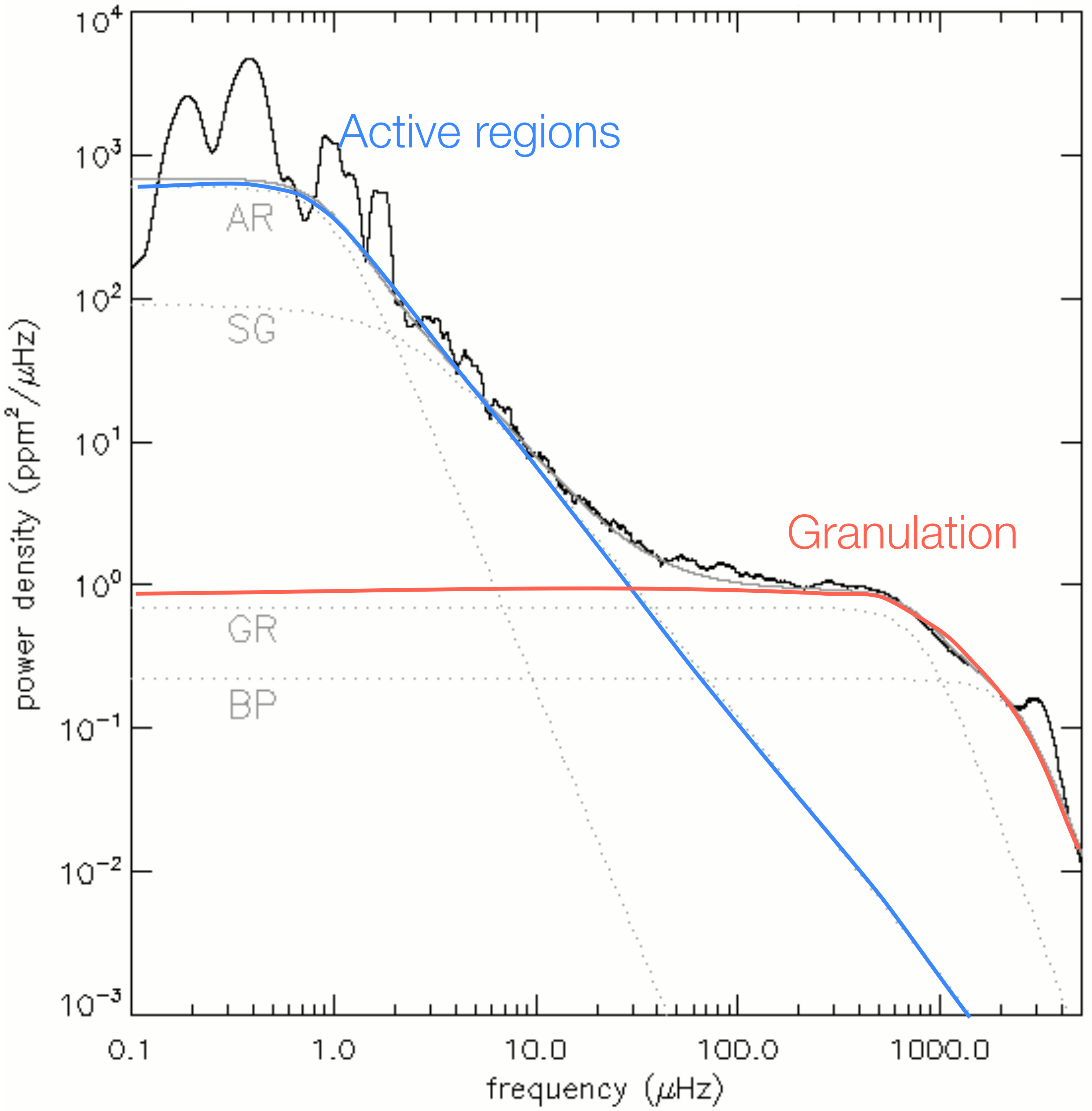
Solar irradiance (SoHO/VIRGO)



(Aigrain, Favata & Gilmore 2004)

Timescales

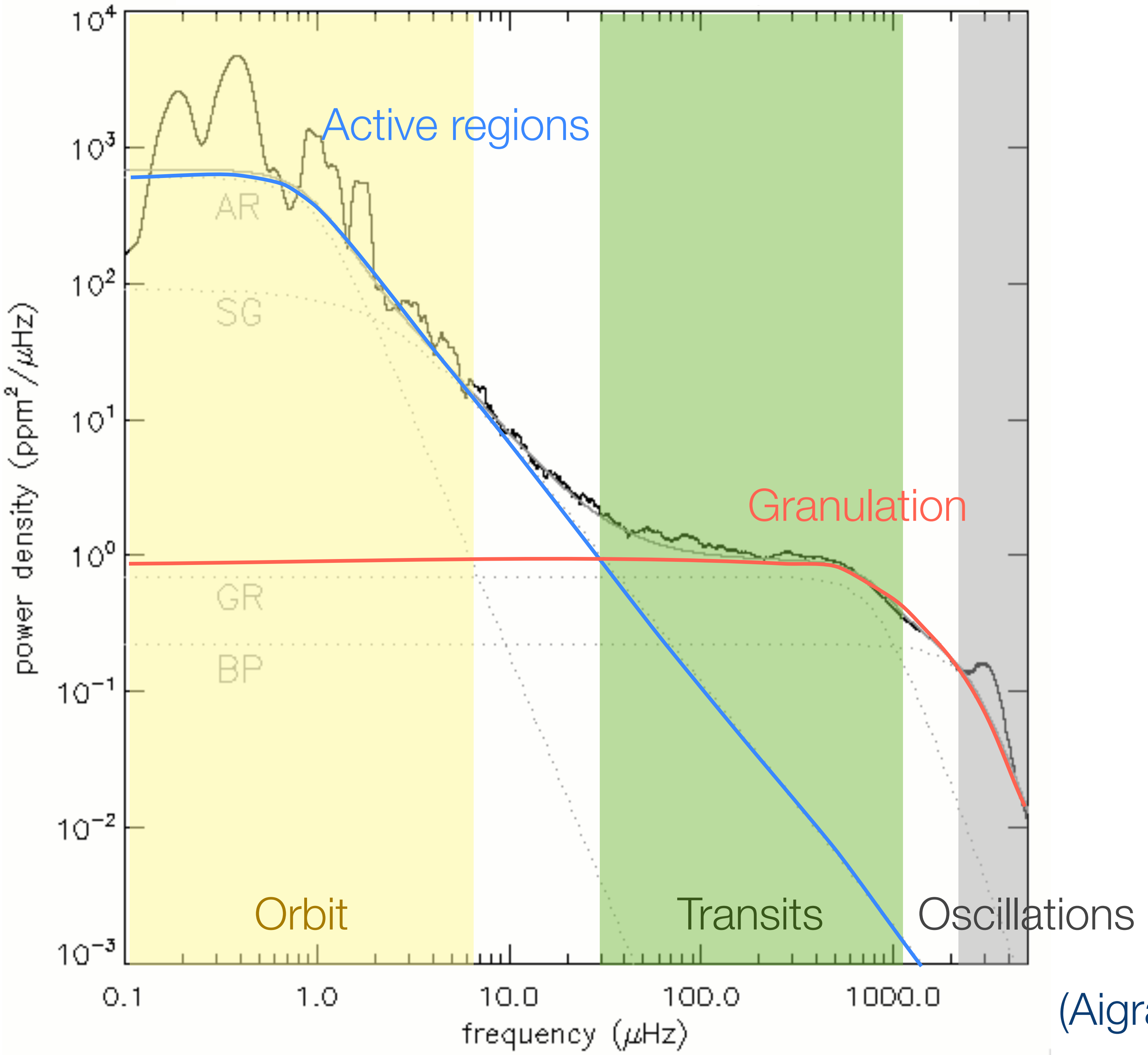
Solar irradiance (SoHO/VIRGO)



(Aigrain, Favata & Gilmore 2004)

Timescales

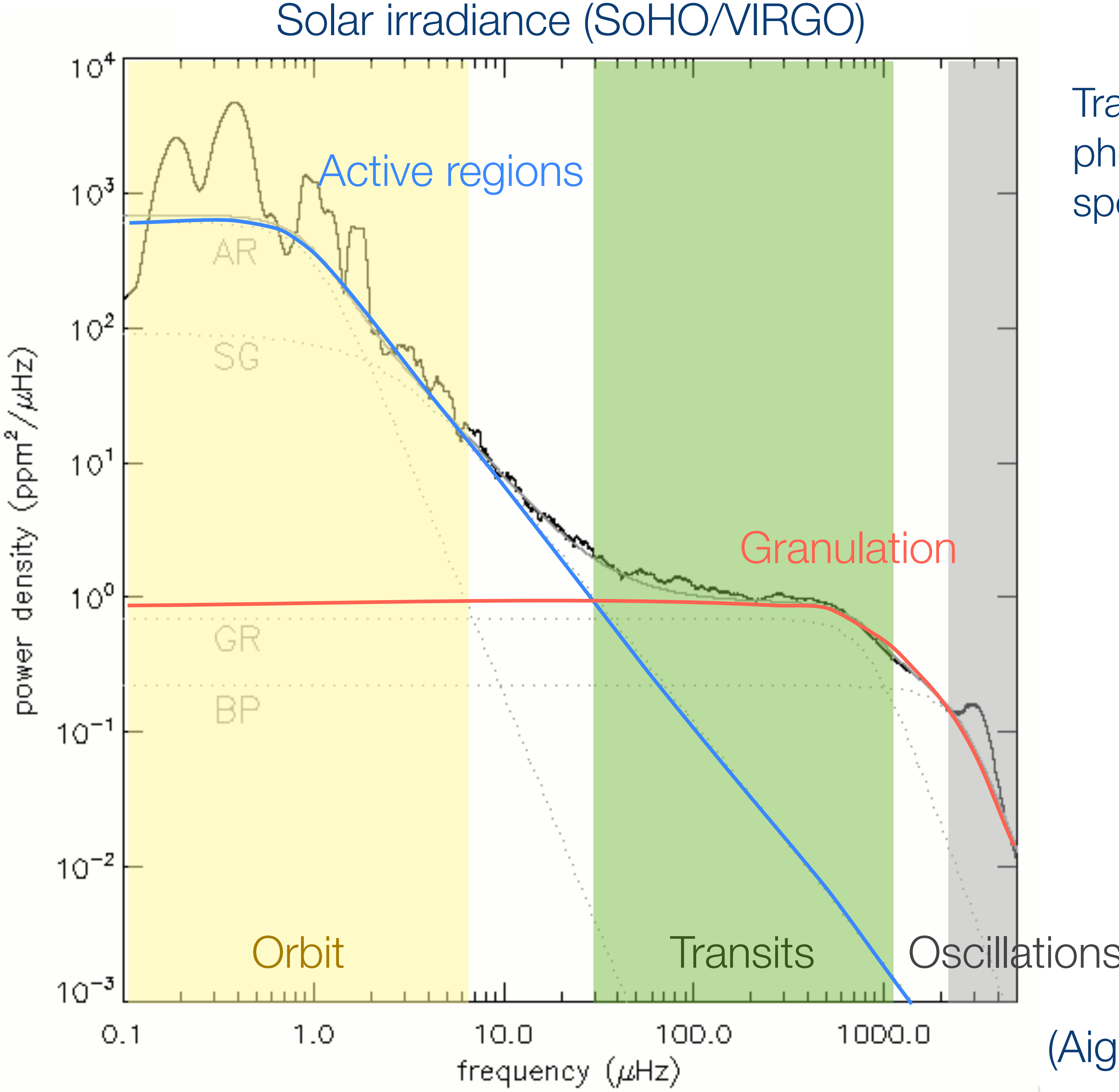
Solar irradiance (SoHO/VIRGO)



(Aigrain, Favata & Gilmore 2004)

Timescales

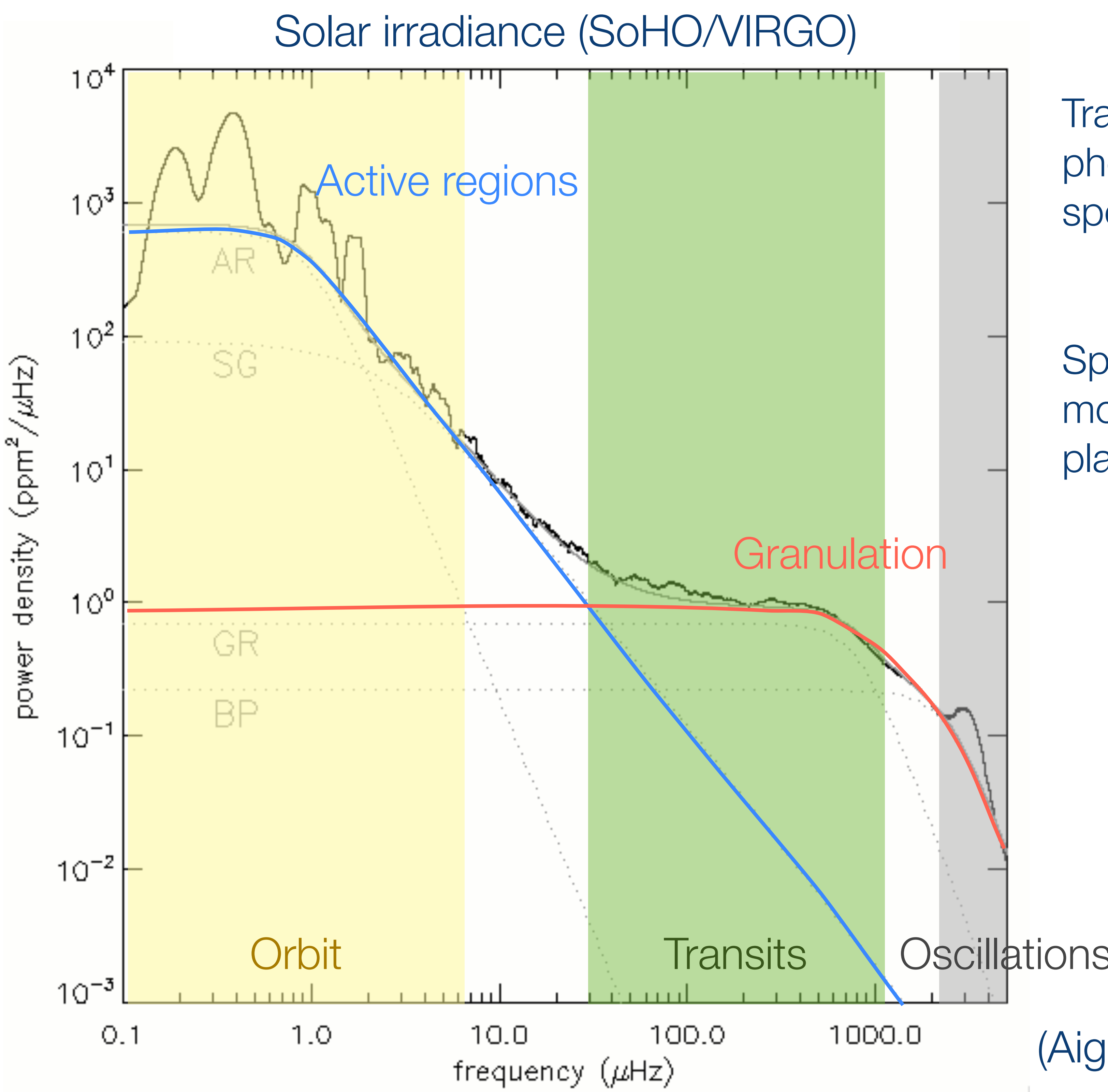
Solar irradiance (SoHO/VIRGO)



Transits are easy to separate from photometric variations due to start spots … up to a point!

(Aigrain, Favata & Gilmore 2004)

Timescales

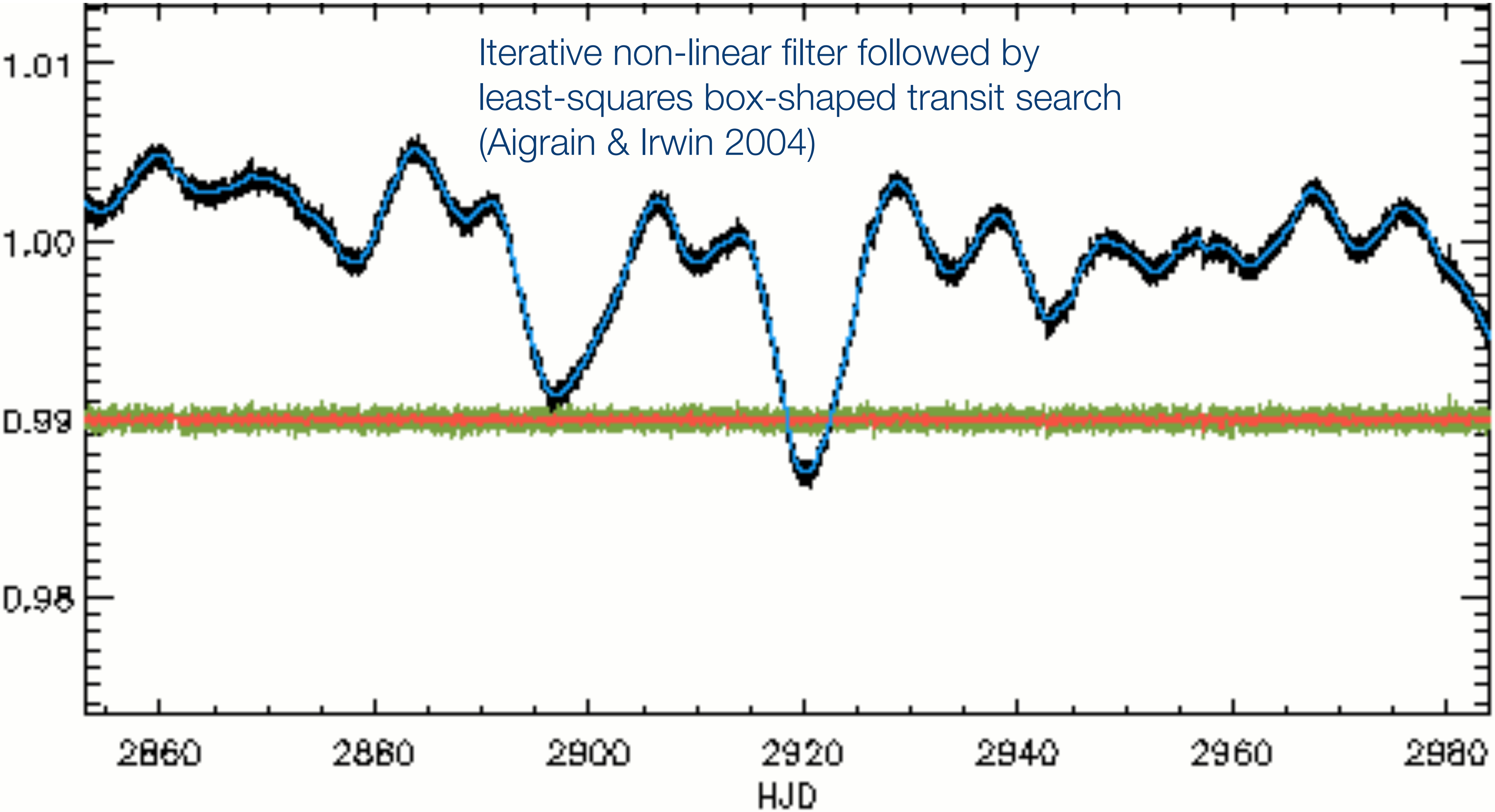


Transits are easy to separate from photometric variations due to start spots … up to a point!

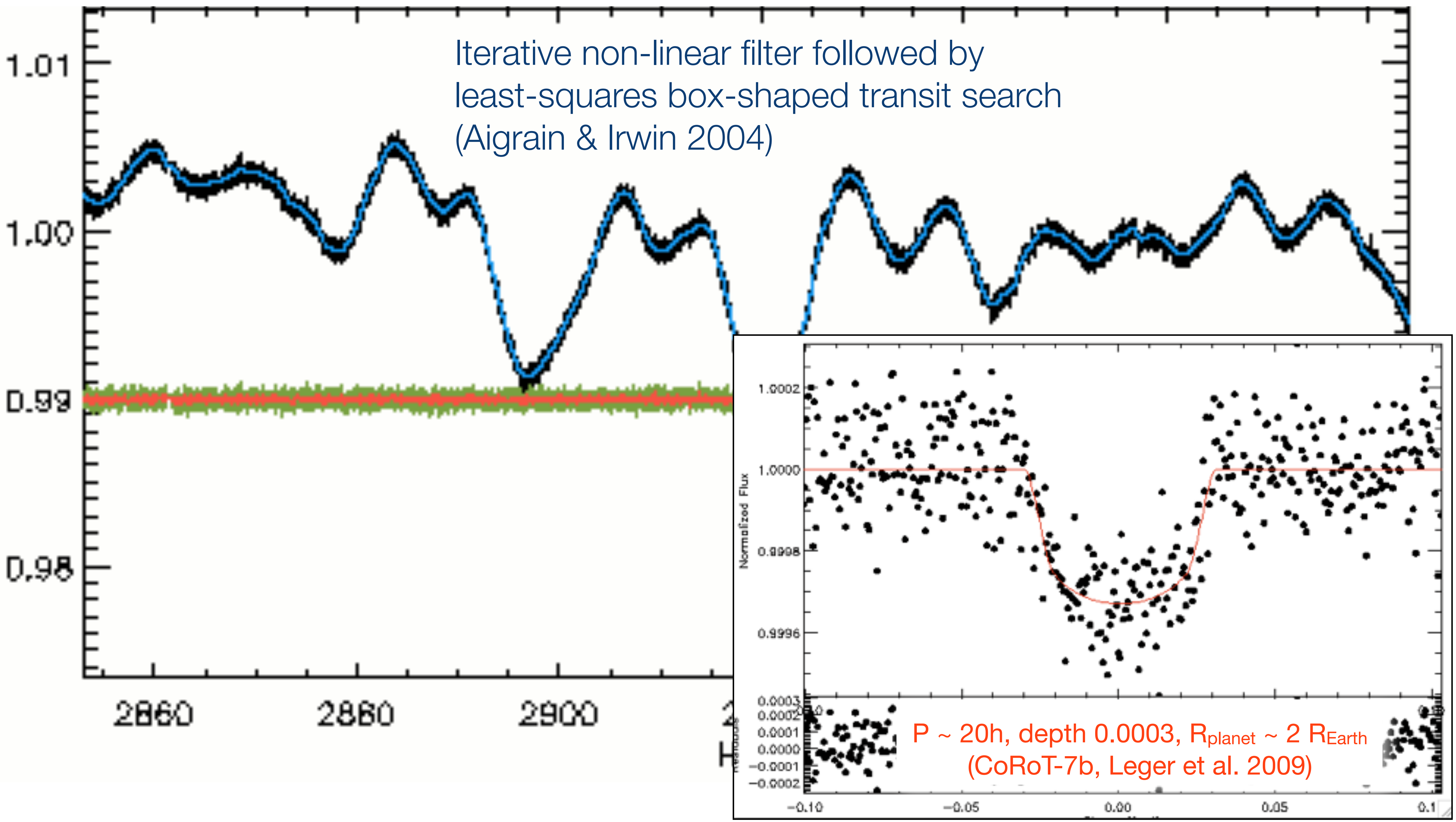
Spot-induced variability is potentially more problematic for radial velocity planet searches

(Aigrain, Favata & Gilmore 2004)

Filtering activity to detect transits



Filtering activity to detect transits



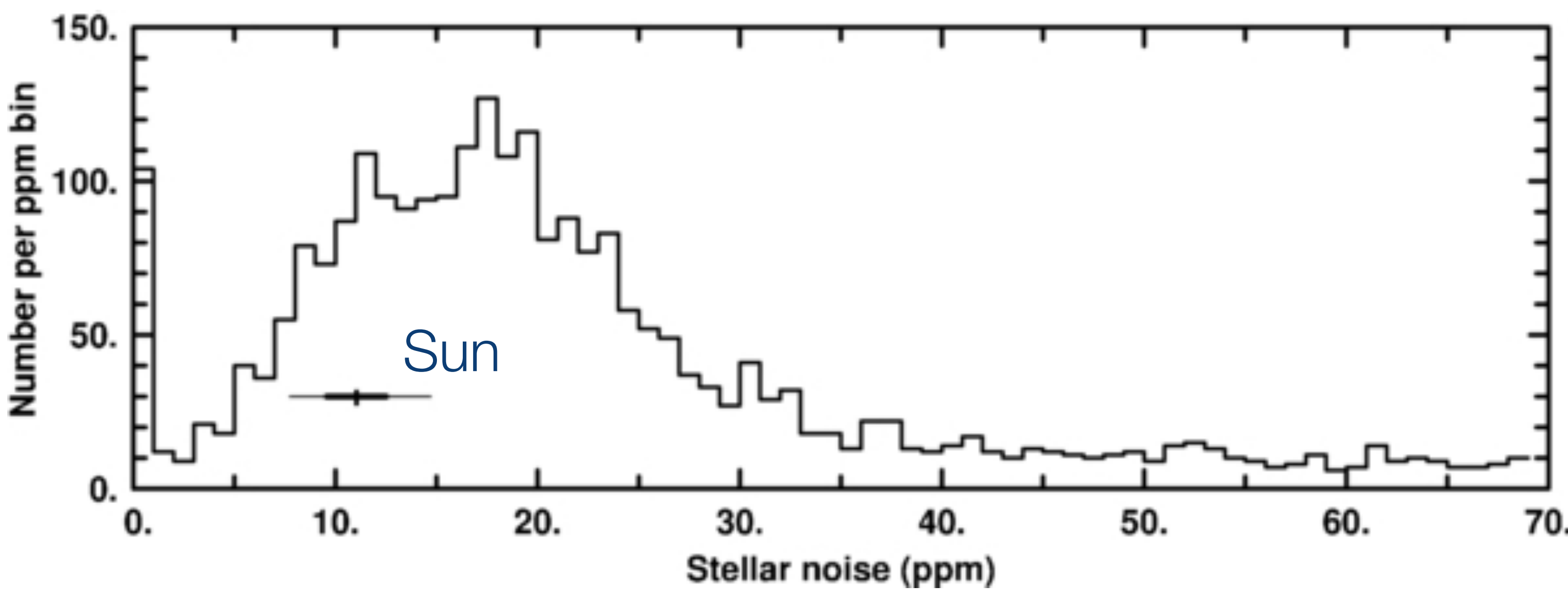
When does activity matter for transit searches?

Transit SNR =
$\mathrm{sqrt}(N_{transits})$ x depth / $\mathrm{sigma}(T_{transit})$
where:
- $N_{transits}$ is number of transits
- $T_{transit}$ is duration of transit

When does activity matter for transit searches?

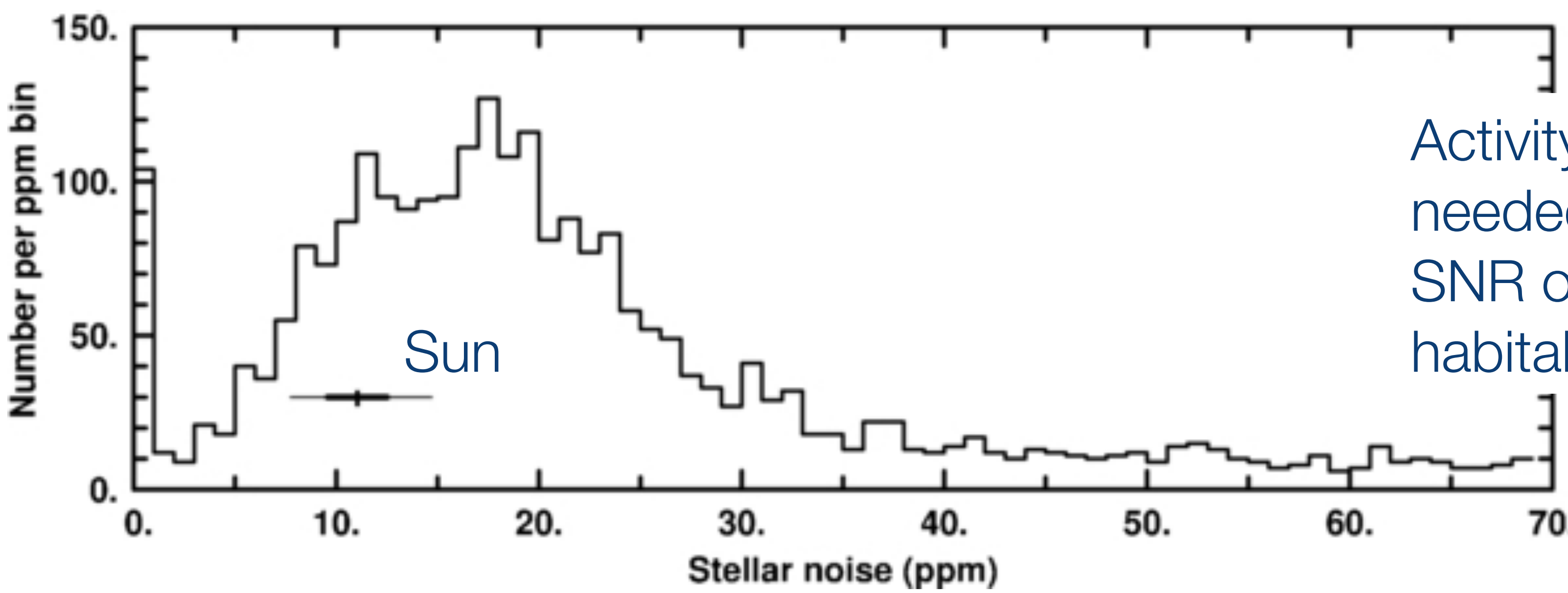
Transit SNR =
sqrt($N_{transits}$) x depth / sigma($T_{transit}$)
where:
- $N_{transits}$ is number of transits
- $T_{transit}$ is duration of transit

Intrinsic stellar variability on 6 hour time-scales from Kepler (Gilliland et al. 2011)



When does activity matter for transit searches?

Intrinsic stellar variability on 6 hour time-scales from Kepler (Gilliland et al. 2011)

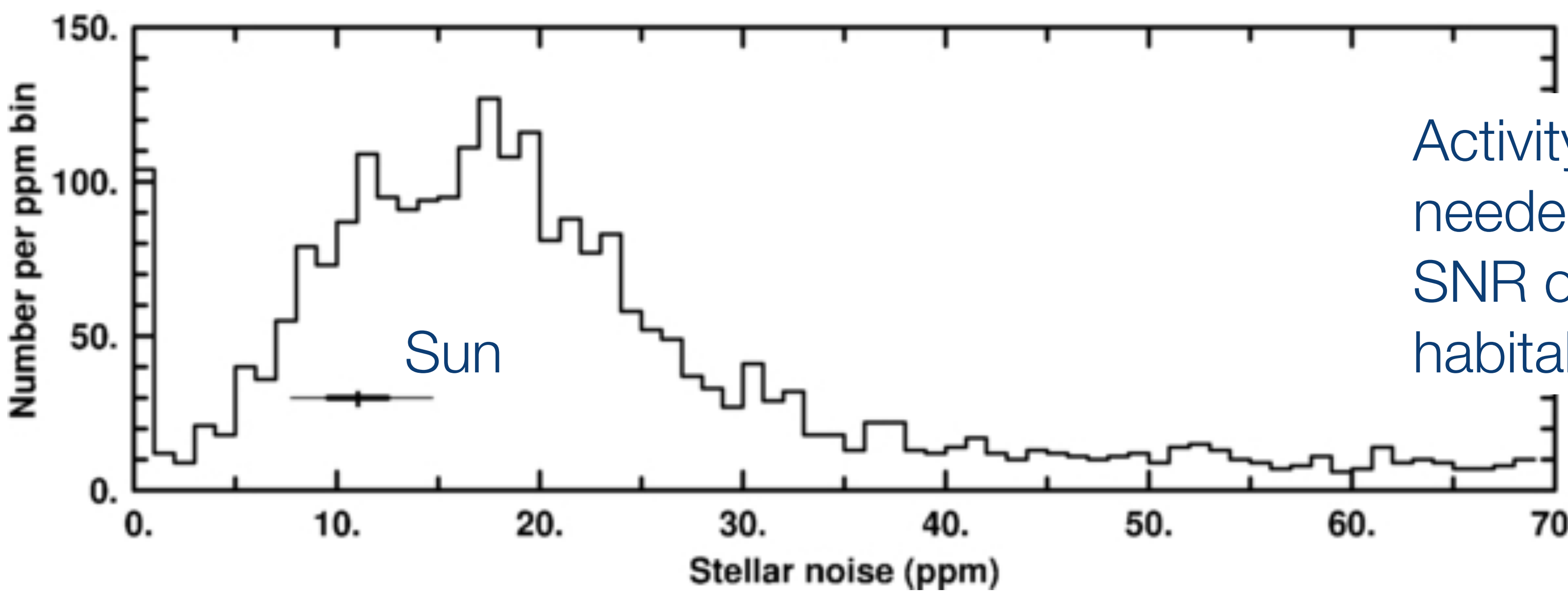


Transit SNR =
$\mathrm{sqrt}(N_{transits}) \times \mathrm{depth} / \mathrm{sigma}(T_{transit})$
where:
- $N_{transits}$ is number of transits
- $T_{transit}$ is duration of transit

Activity means Kepler would have needed 7 rather than 4 years to reach SNR of 10 for Earth-like planets in the habitable zone of Sun-like stars

When does activity matter for transit searches?

Intrinsic stellar variability on 6 hour time-scales from Kepler (Gilliland et al. 2011)



Transit SNR =
sqrt($N_{transits}$) x depth / sigma($T_{transit}$)
where:

- $N_{transits}$ is number of transits
- $T_{transit}$ is duration of transit

Activity means Kepler would have needed 7 rather than 4 years to reach SNR of 10 for Earth-like planets in the habitable zone of Sun-like stars

This can be addressed, at least partially, by *modelling* the activity-induced variations *simultaneously* with the transits

Computationally expensive, though!

Kepler data is ideal to measure stellar rotation periods

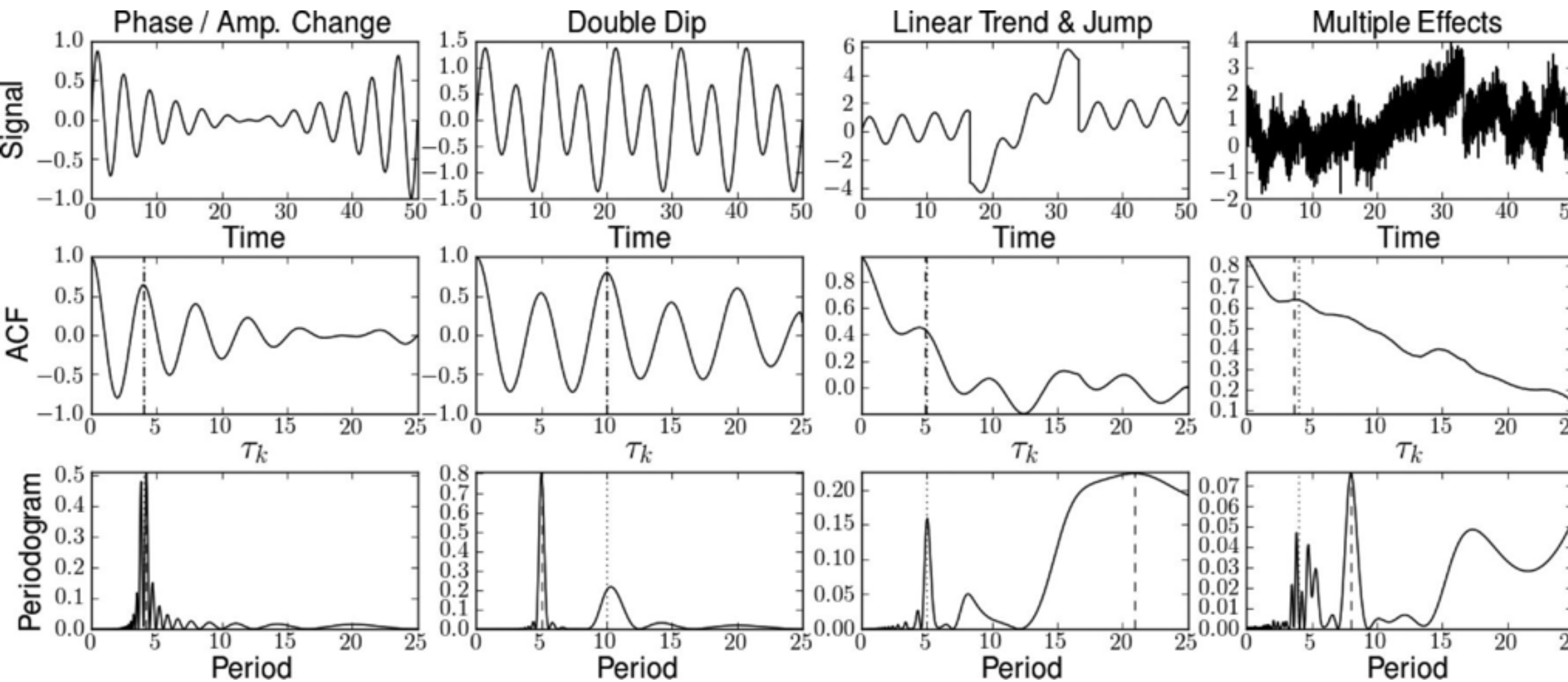
Very high precision, 4 year baseline, near continuous.

But … we need period-search method that can cope with active region evolution and residual instrumental effects.

Kepler data is ideal to measure stellar rotation periods

Very high precision, 4 year baseline, near continuous.

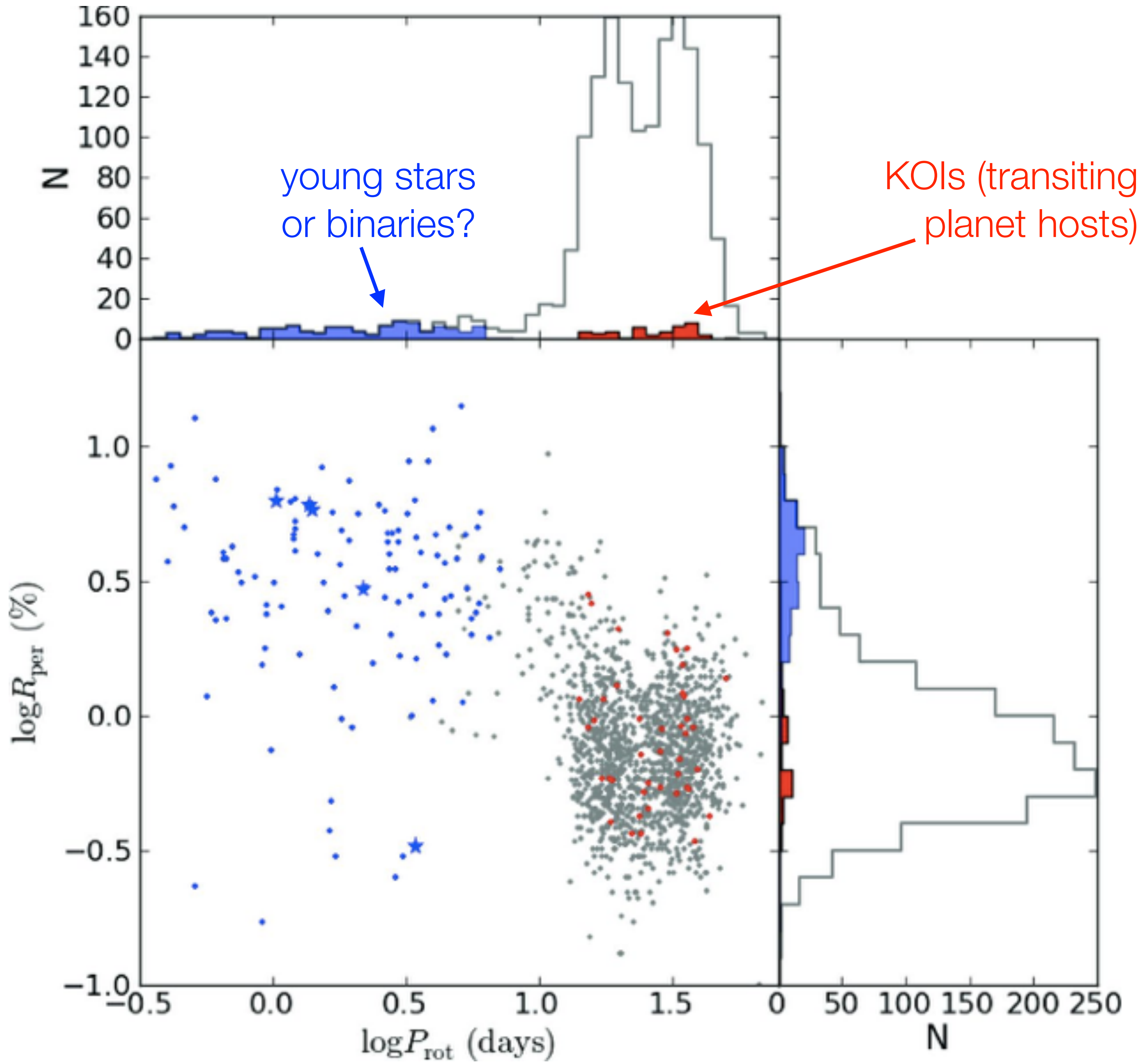
But … we need period-search method that can cope with active region evolution and residual instrumental effects. use auto-correlation function (ACF, McQuillan, Aigrain & Mazeh 2013).



~2500 M-dwarfs

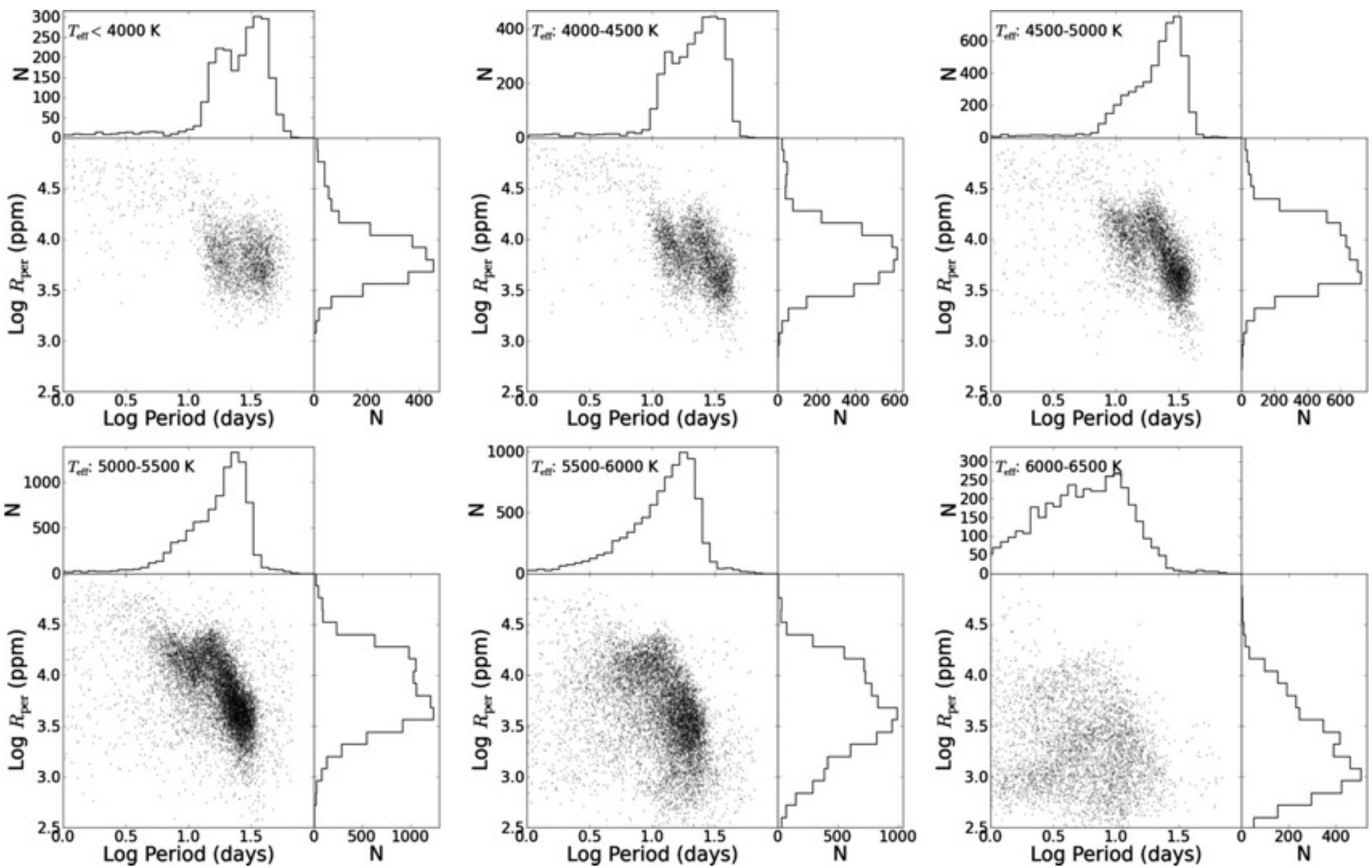
(McQuillan, Aigrain & Mazeh 2013)

Note bimodal
period distribution



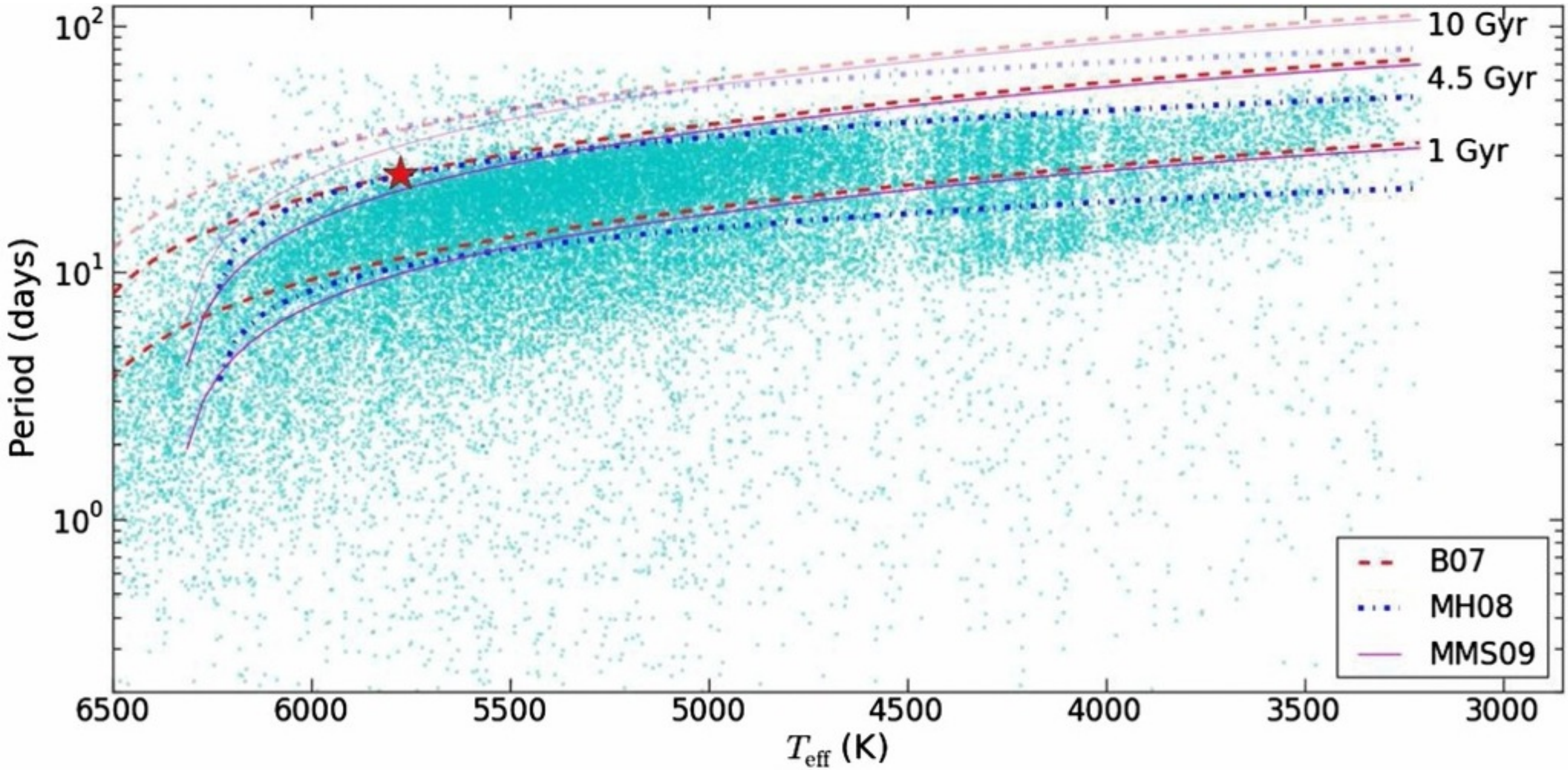
33400 FGKM dwarfs

(McQuillan, Mazeh & Aigrain 2014)



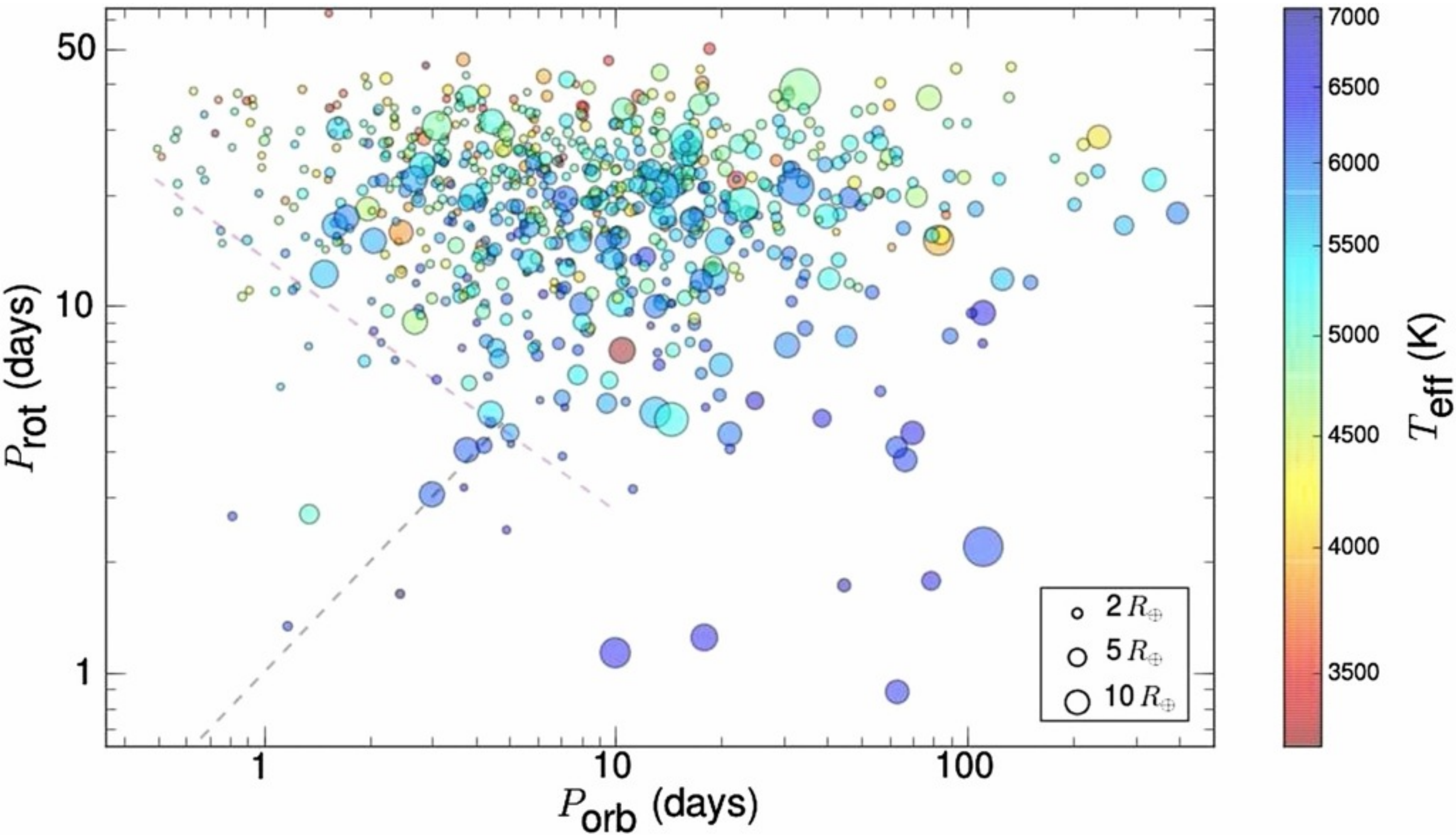
33400 FGKM dwarfs

(McQuillan, Mazeh & Aigrain 2014)

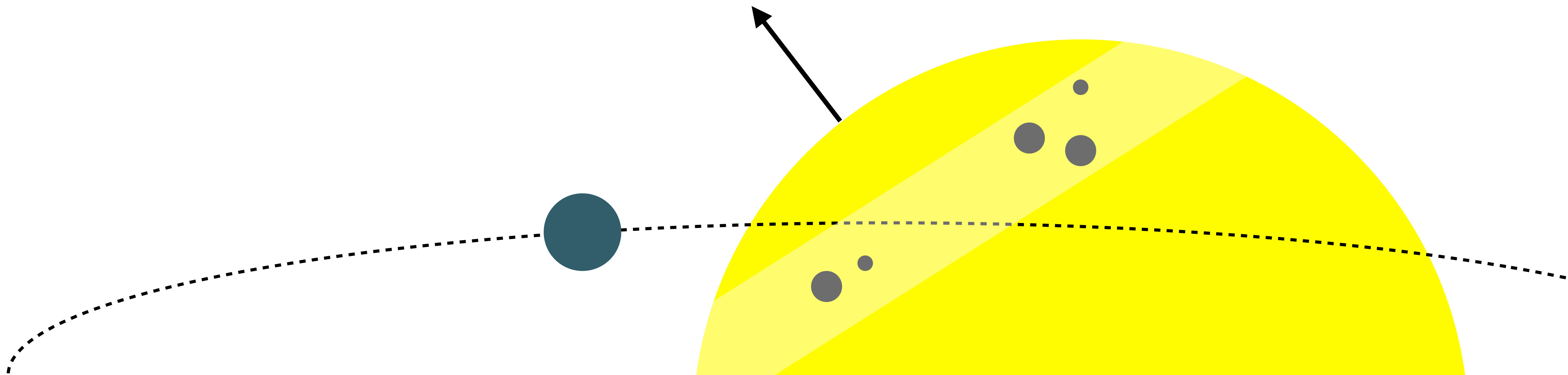


~2500 planet host stars

Dearth of short-period planets around rapidly rotating stars
(McQuillan, Mazeh & Aigrain 2013)



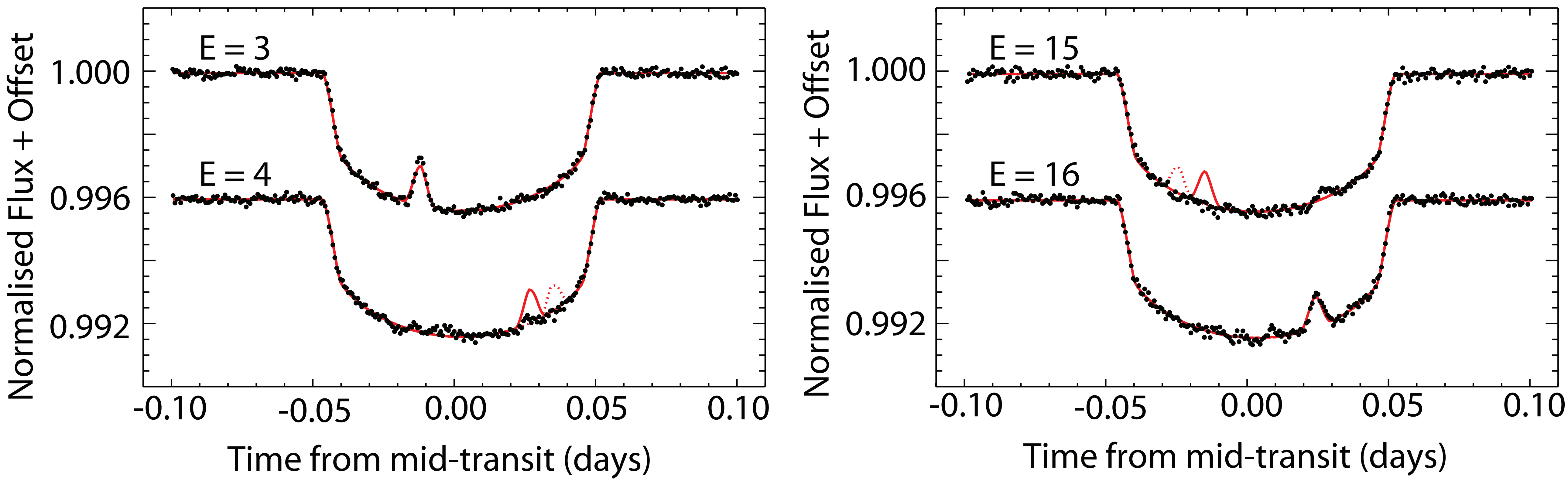
Spot mapping by transits

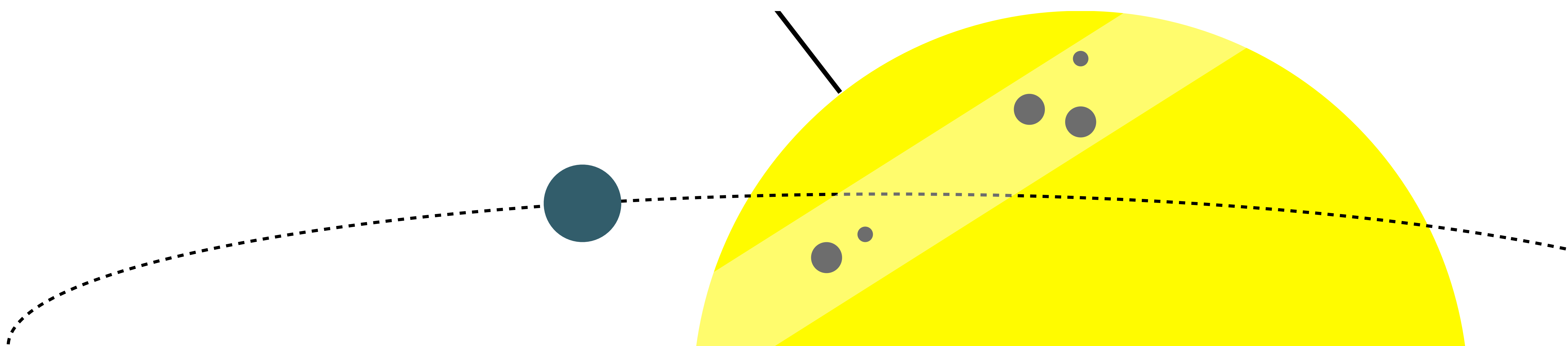


Spot mapping by transits

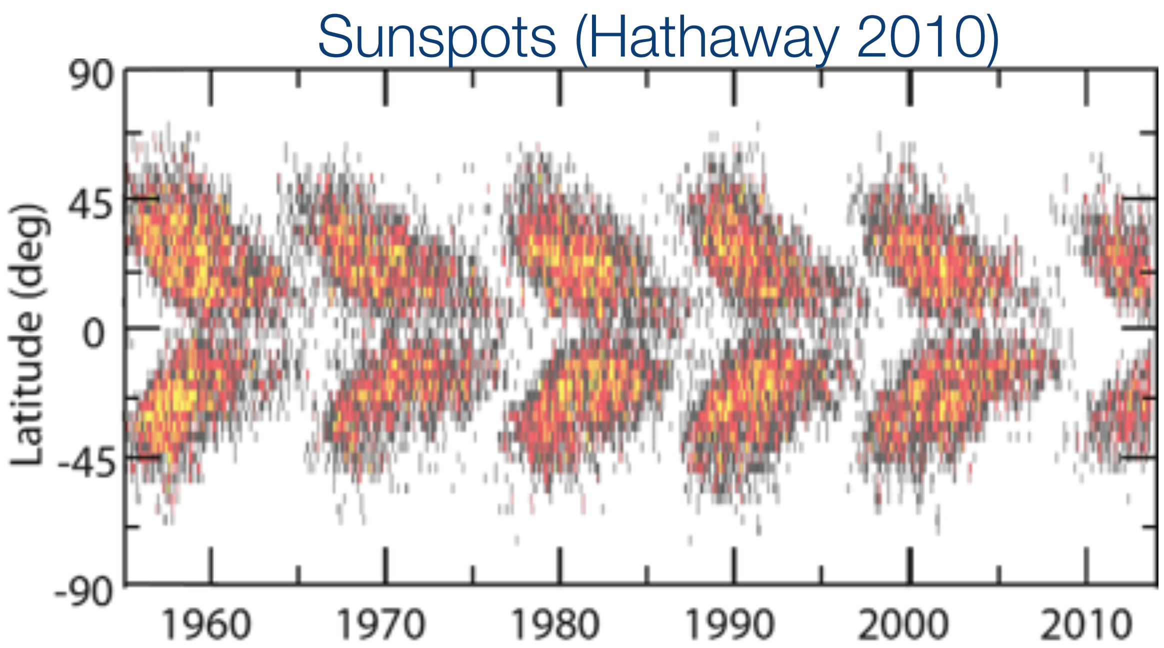
Spots occulted during multiple transits can be used to derive projected spin-orbit angle (Sanchis-Ojeda et al. 2011)

HAT-P-11

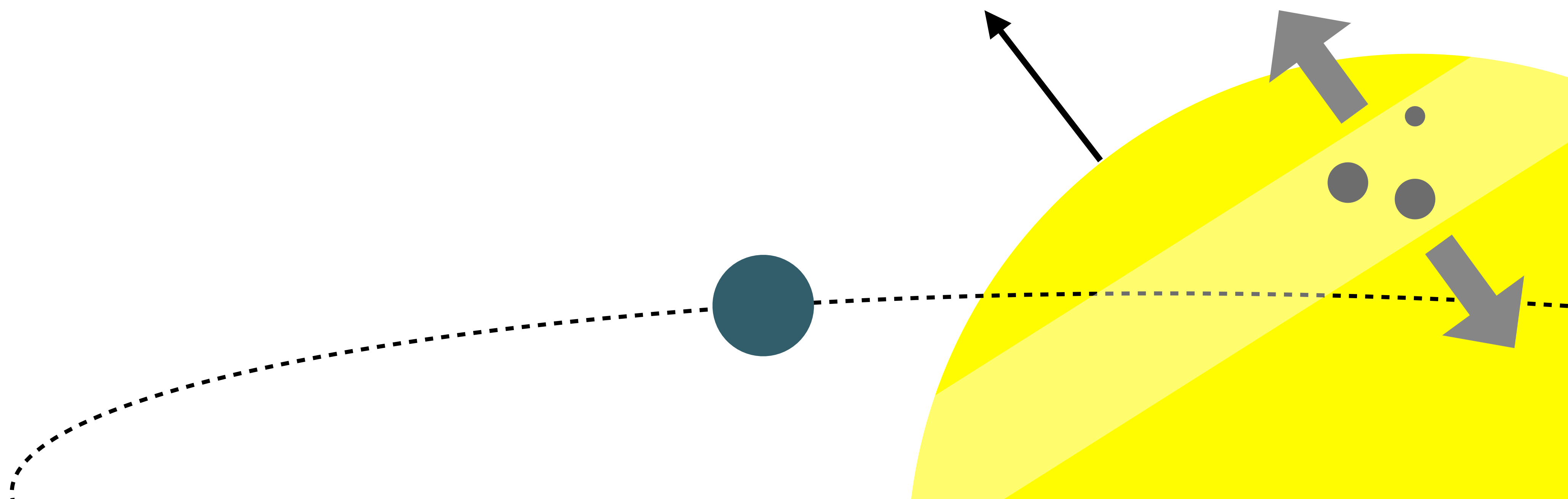




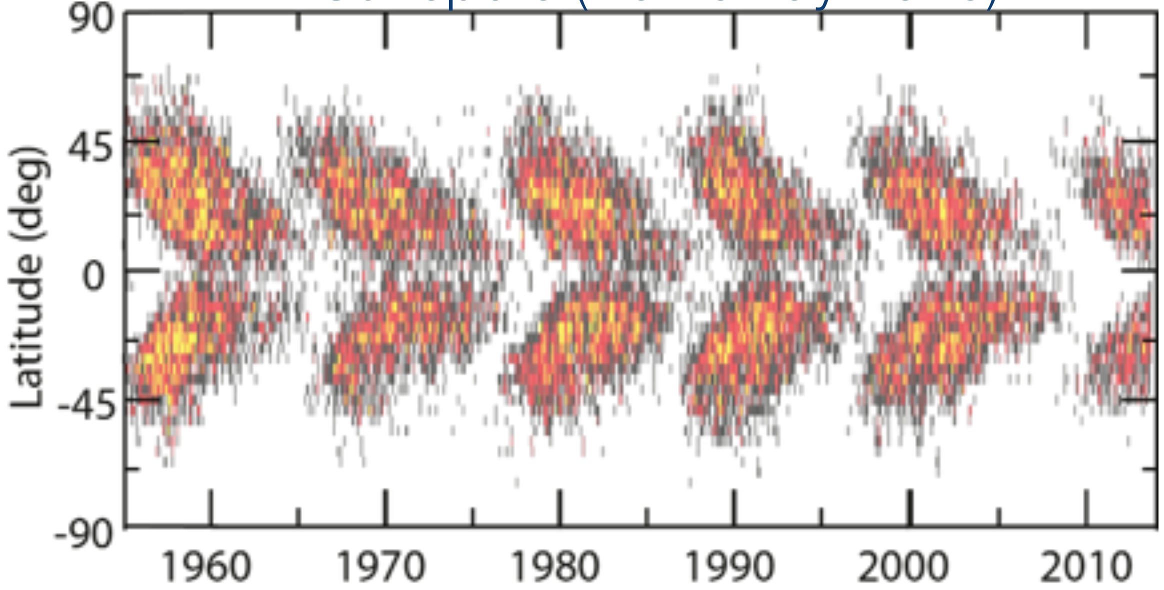
Spot mapping by transits



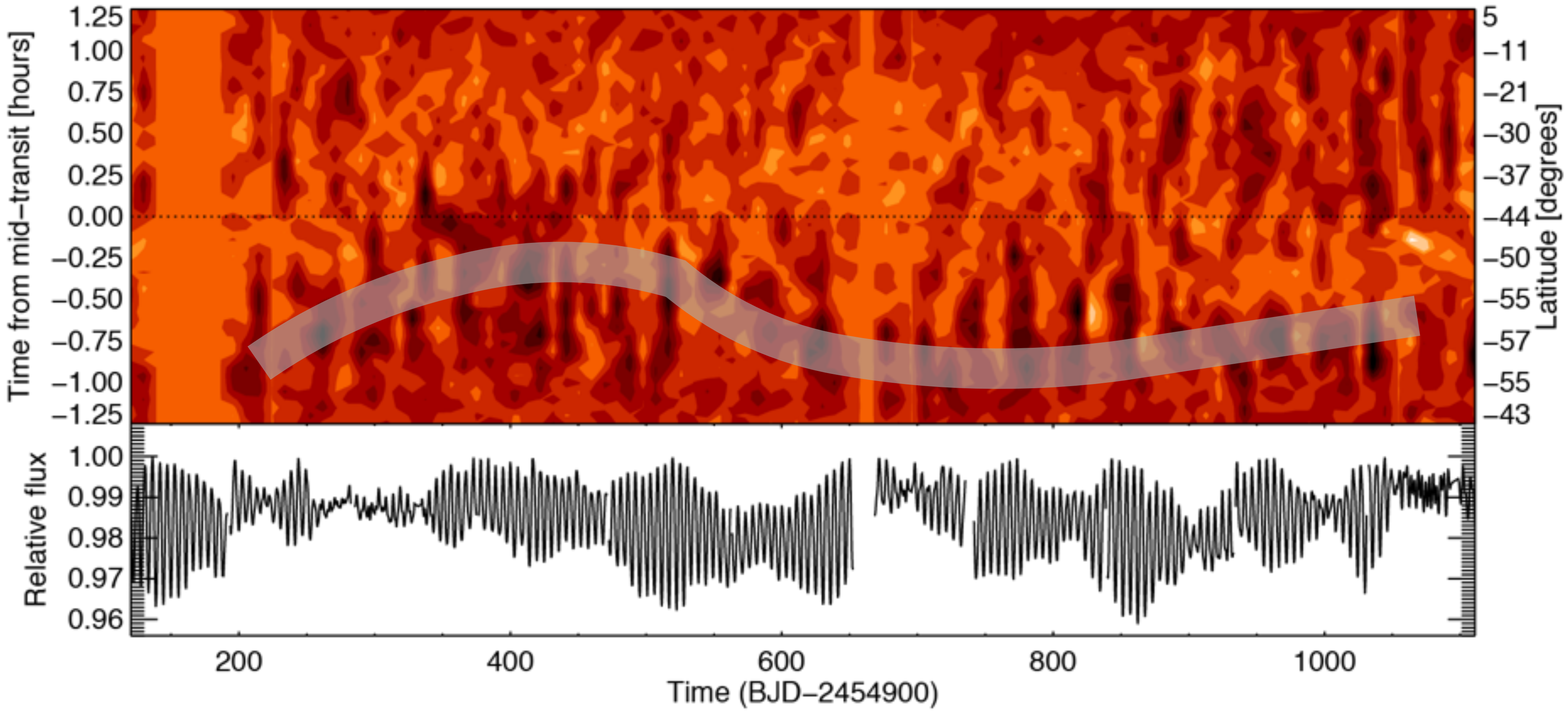
Spots occulted during many transits can reveal butterfly patterns (Sanchis-Ojeda et al. 2013)



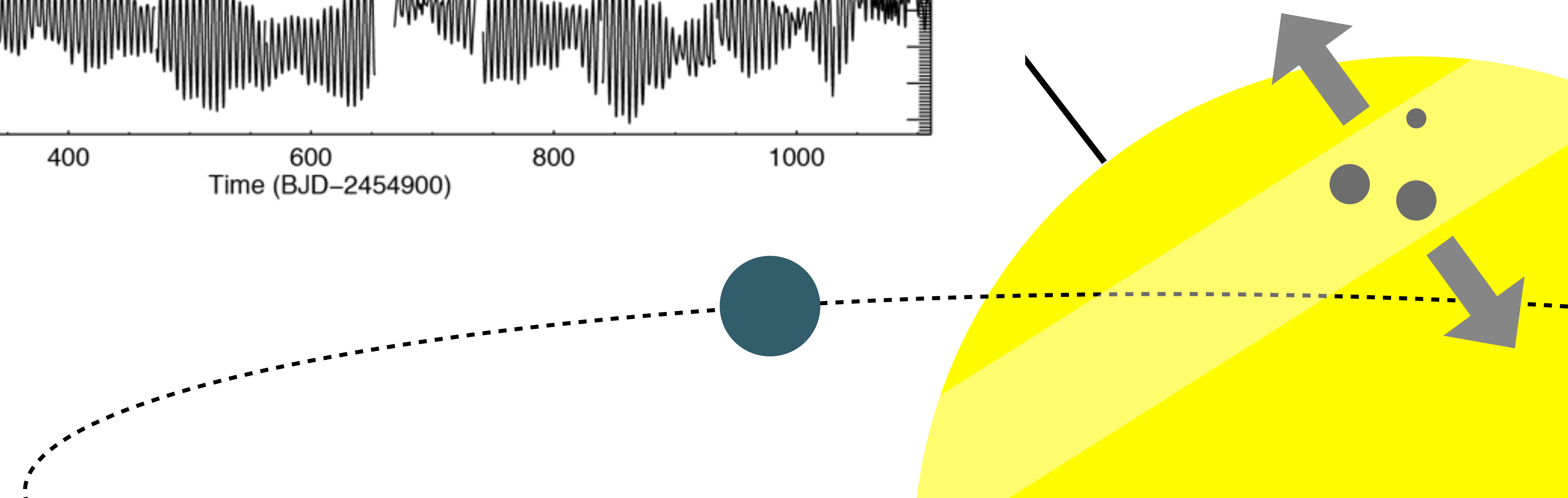
Spot mapping by transits



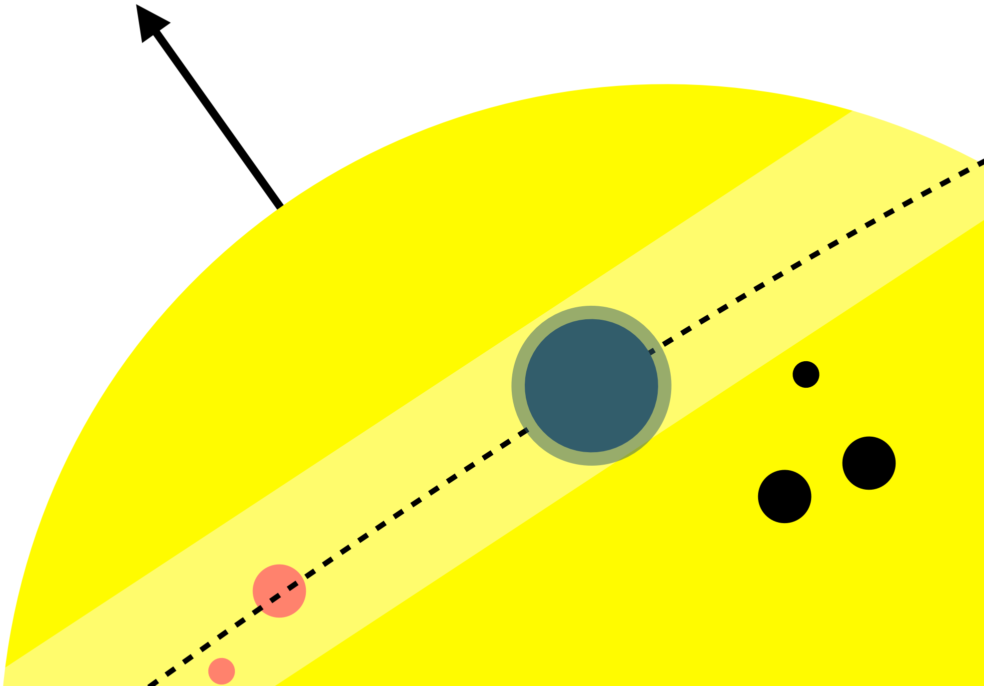
Spots occulted during many transits can reveal butterfly patterns (Sanchis-Ojeda et al. 2013)



Kepler 63

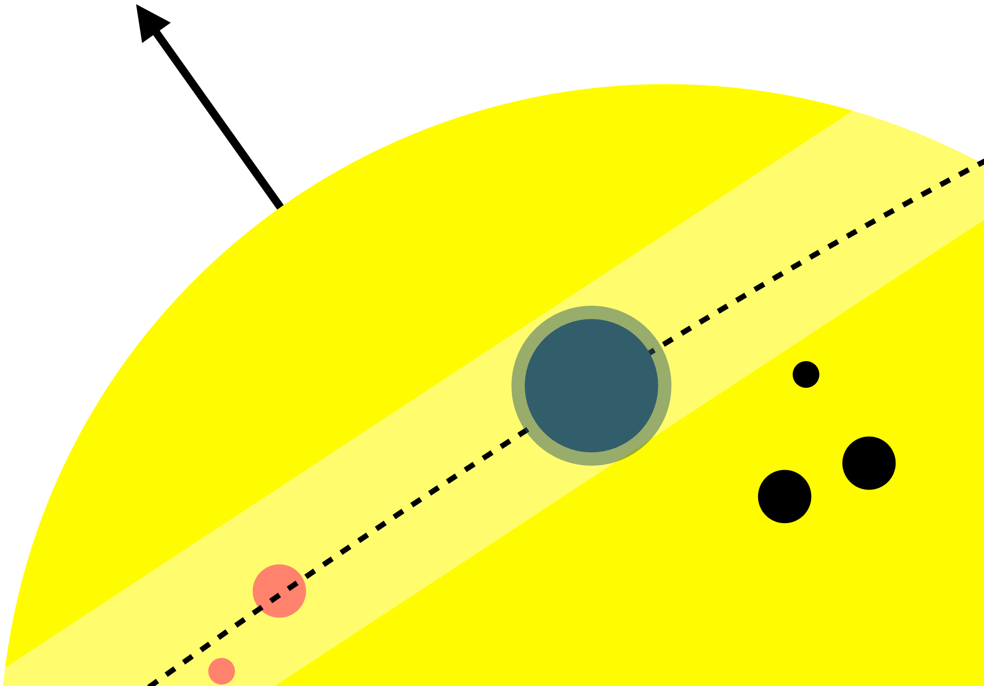


Transmission spectroscopy



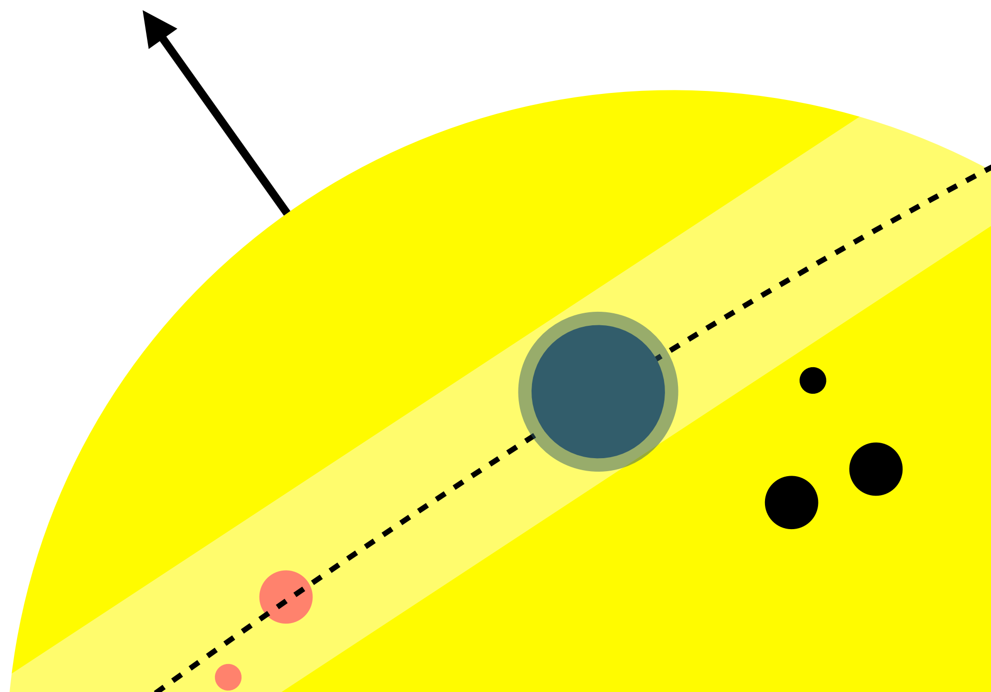
Transmission spectroscopy

- Measure transit depth (i.e. altitude at which planet becomes opaque) vs wavelength
    - alternatively, compare spectrum of star in- and out-of-transit



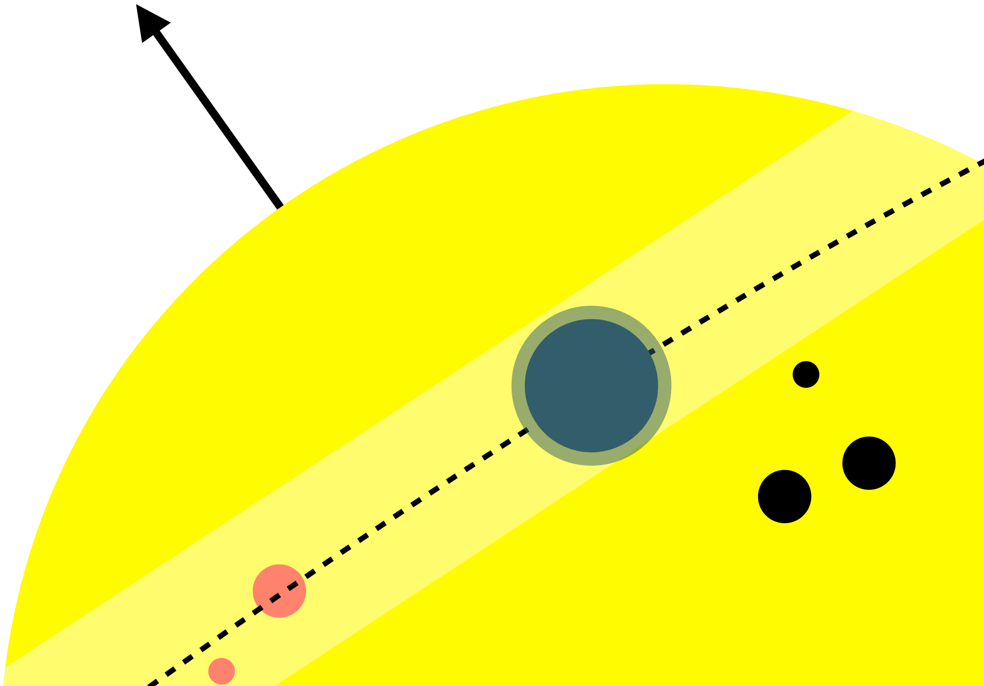
Transmission spectroscopy

- Measure transit depth (i.e. altitude at which planet becomes opaque) vs wavelength
    - alternatively, compare spectrum of star in- and out-of-transit
- Powerful probe of composition of planet atmosphere: gases and particulates



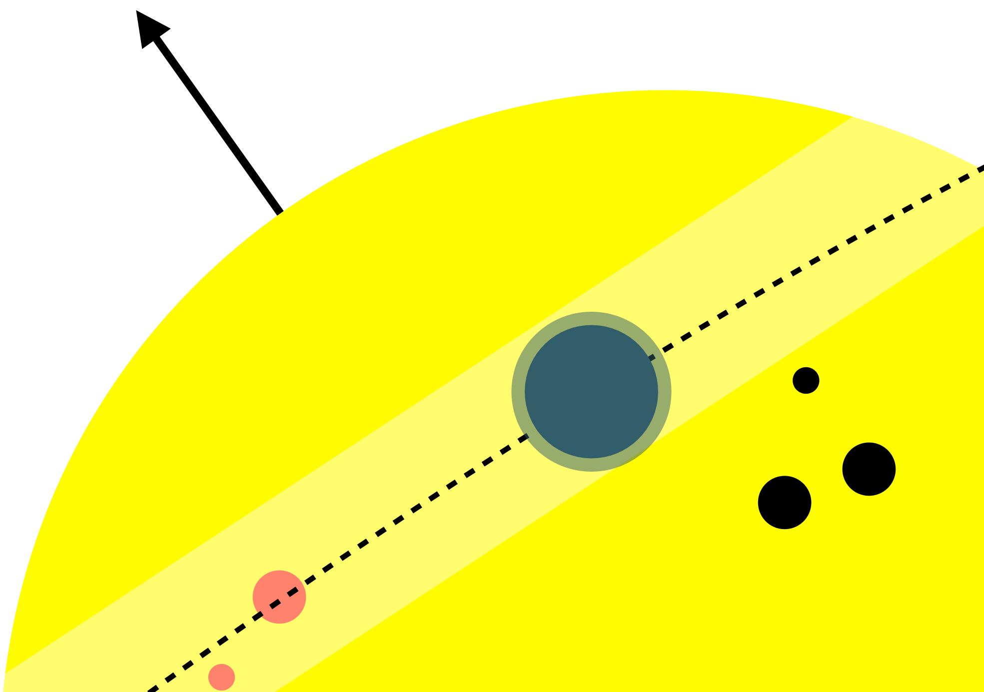
Transmission spectroscopy

- Measure transit depth (i.e. altitude at which planet becomes opaque) vs wavelength
  - alternatively, compare spectrum of star in- and out-of-transit
- Powerful probe of composition of planet atmosphere: gases and particulates
- But: spotted parts of star have different spectrum…



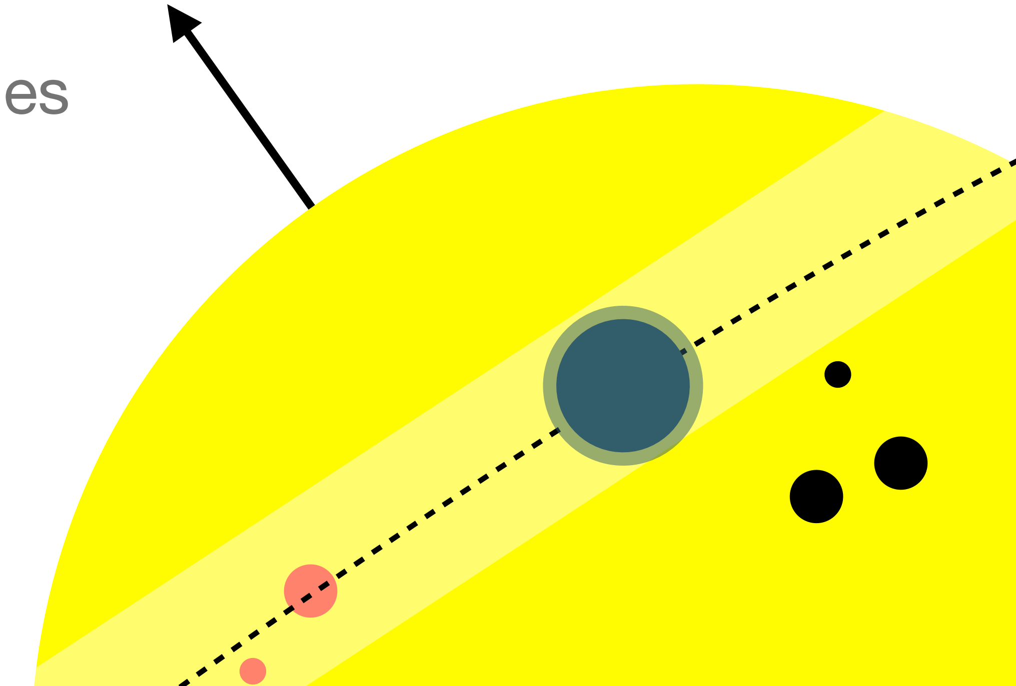
Transmission spectroscopy

- Measure transit depth (i.e. altitude at which planet becomes opaque) vs wavelength
  - alternatively, compare spectrum of star in- and out-of-transit
- Powerful probe of composition of planet atmosphere: gases and particulates
- But: spotted parts of star have different spectrum…
- Need to worry about two kinds of spots:
  - occulted spots distort transit, or make it seem shallower
  - un-occulted spots make transit appear deeper



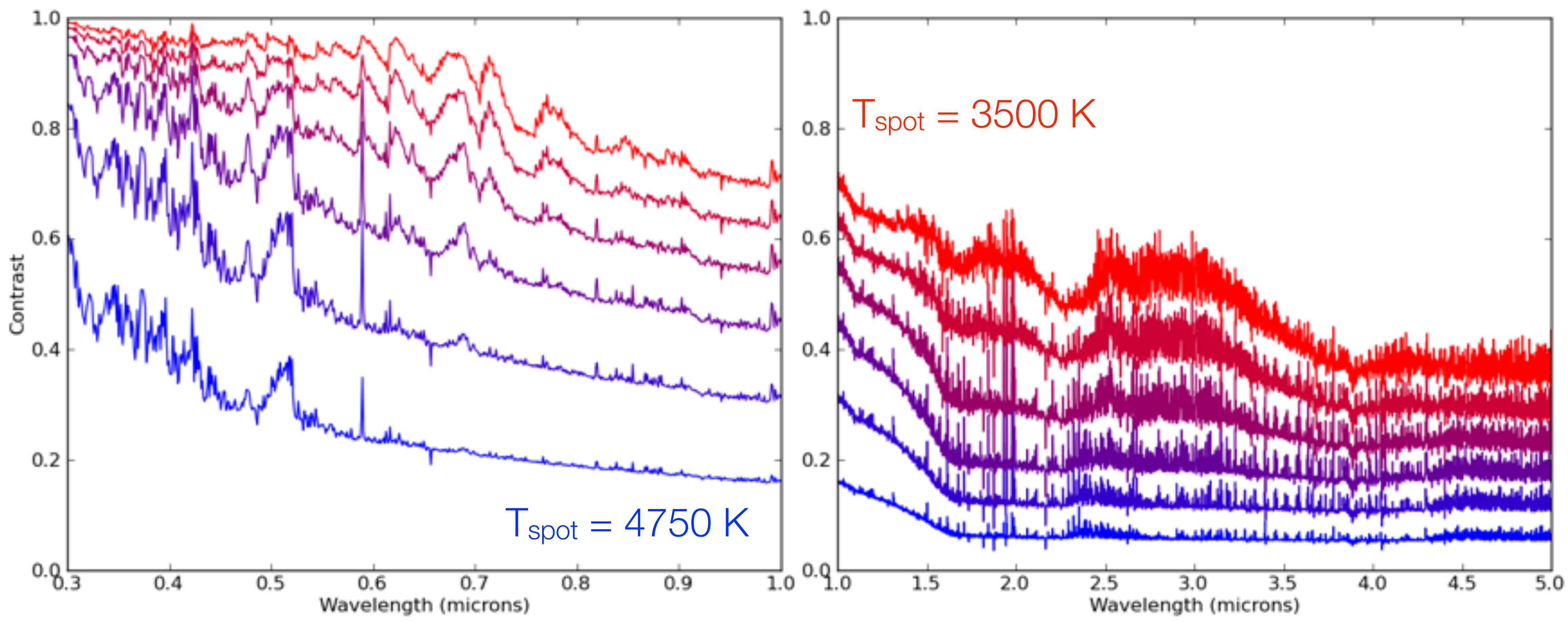
Transmission spectroscopy

- Measure transit depth (i.e. altitude at which planet becomes opaque) vs wavelength
    - alternatively, compare spectrum of star in- and out-of-transit
- Powerful probe of composition of planet atmosphere: gases and particulates
- But: spotted parts of star have different spectrum…
- Need to worry about two kinds of spots:
    - occulted spots distort transit, or make it seem shallower
    - un-occulted spots make transit appear deeper
- Makes it harder to combine obs. taken at different times



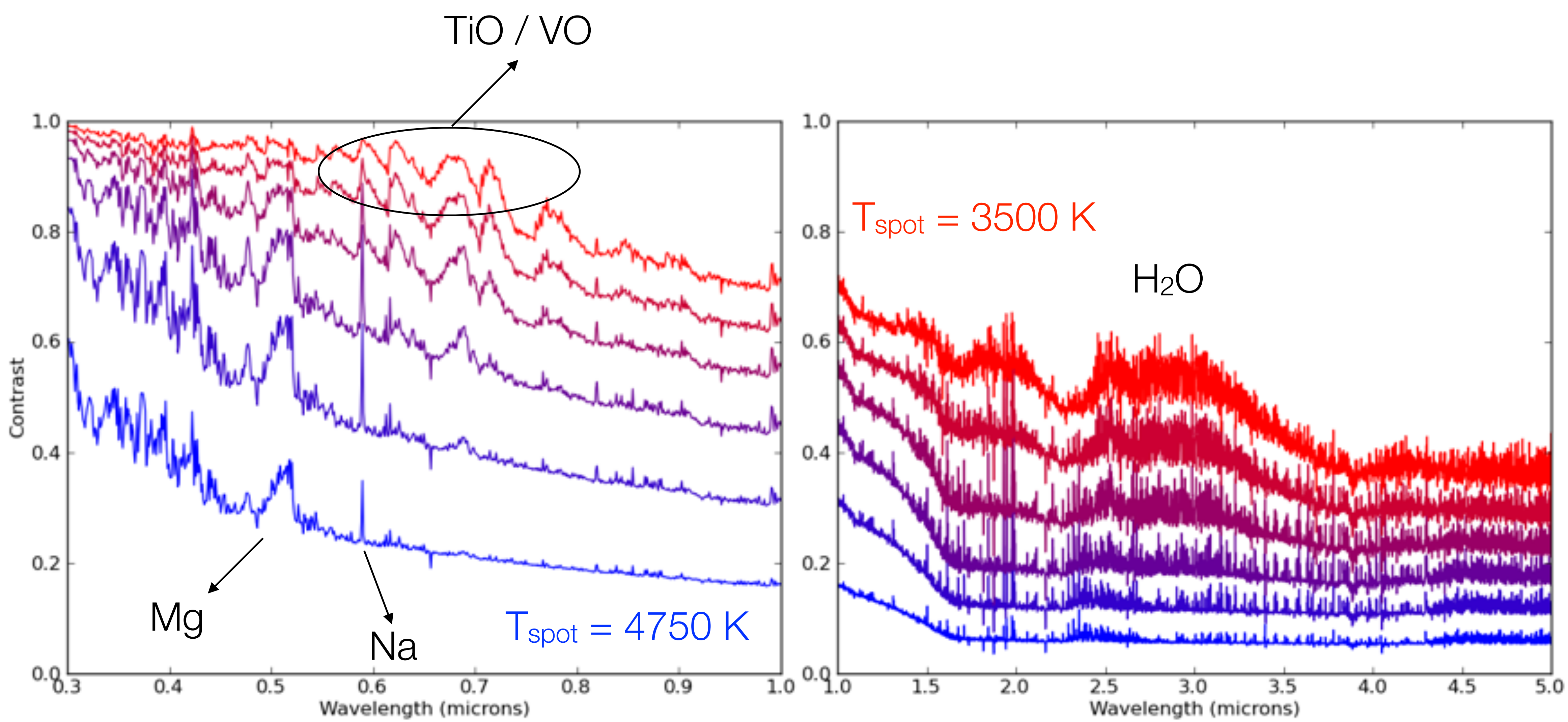
Spectroscopic effects of star spots

Contrast between 5000 K photosphere and cool spots with different temperatures
(MARCS models, Gustafsson et al. 2008, log g = 4.5, [Fe/H] = 0)

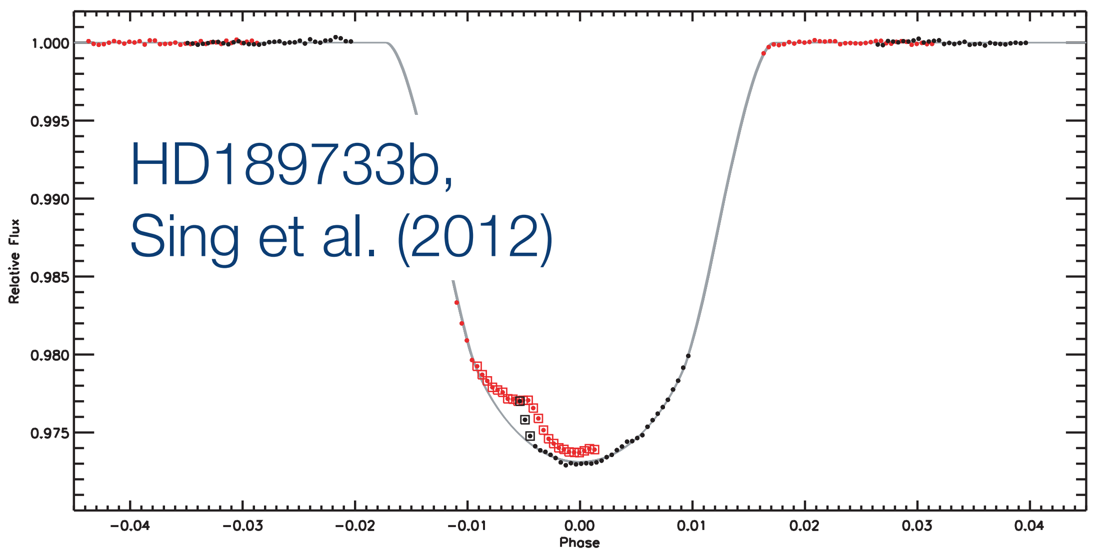


Spectroscopic effects of star spots

Contrast between 5000 K photosphere and cool spots with different temperatures
(MARCS models, Gustafsson et al. 2008, log g = 4.5, [Fe/H] = 0)

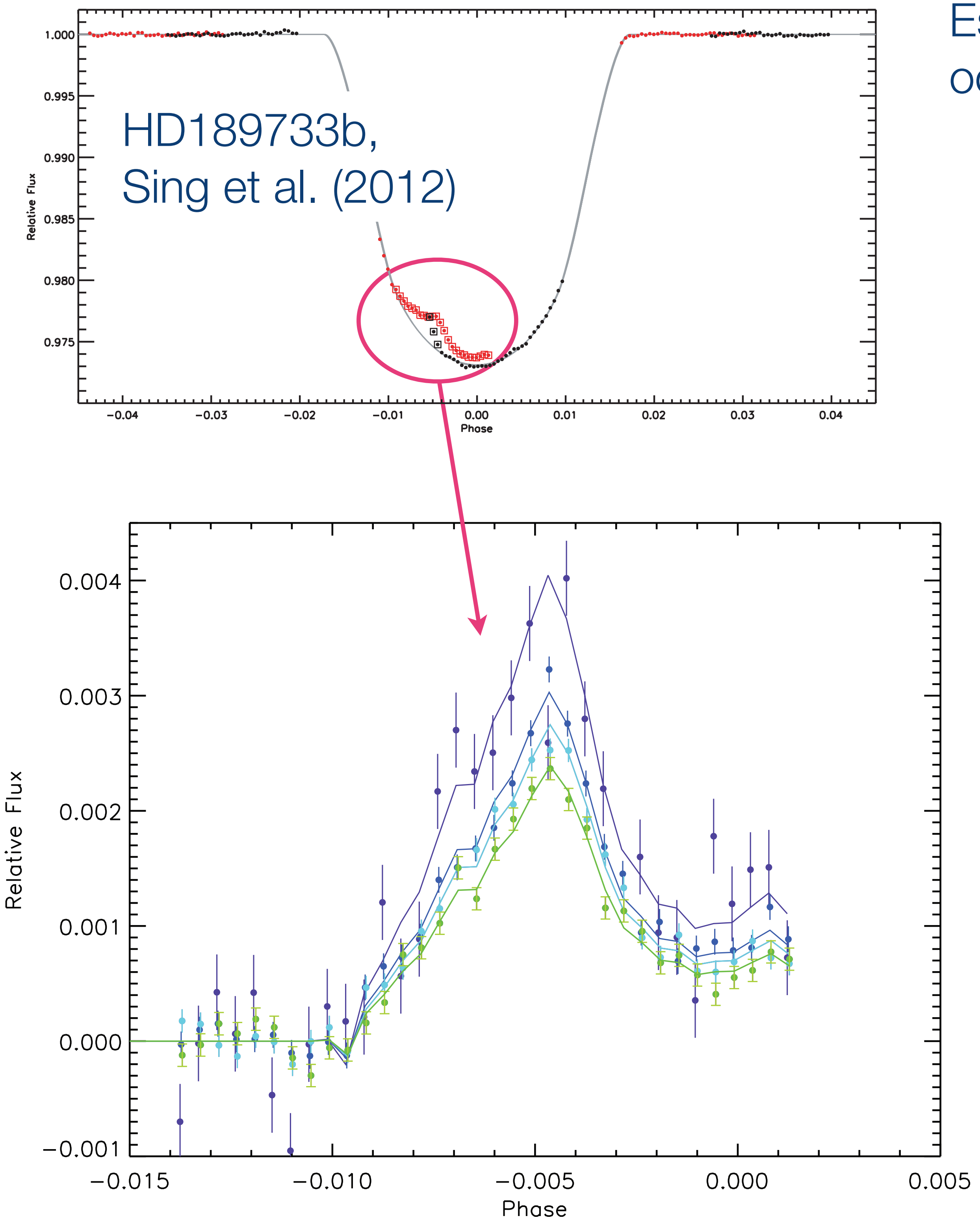


Accounting for spots in transmission spectra



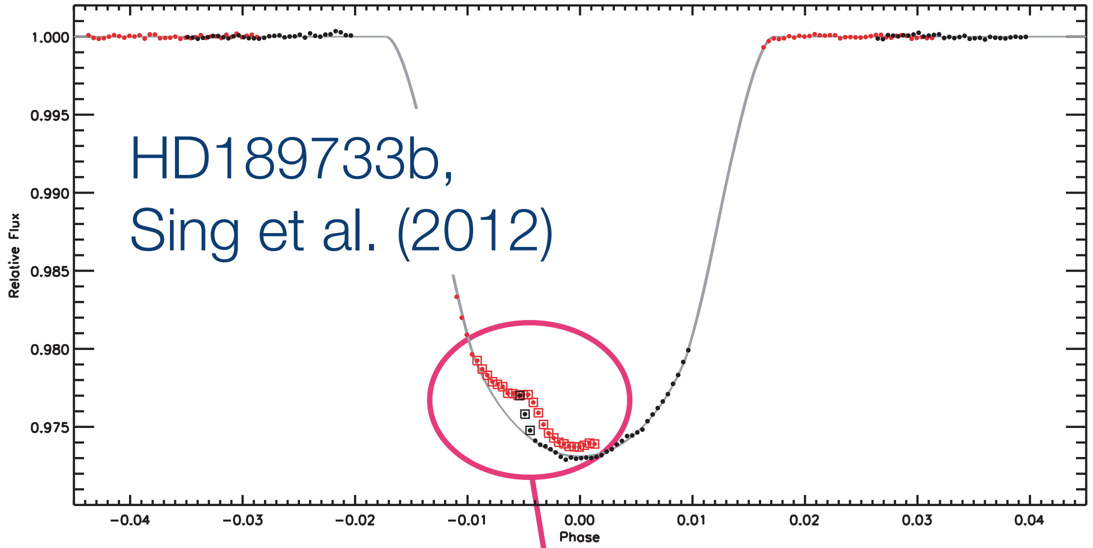
Estimate spectrum/temperature of spots from occulted spots

Accounting for spots in transmission spectra

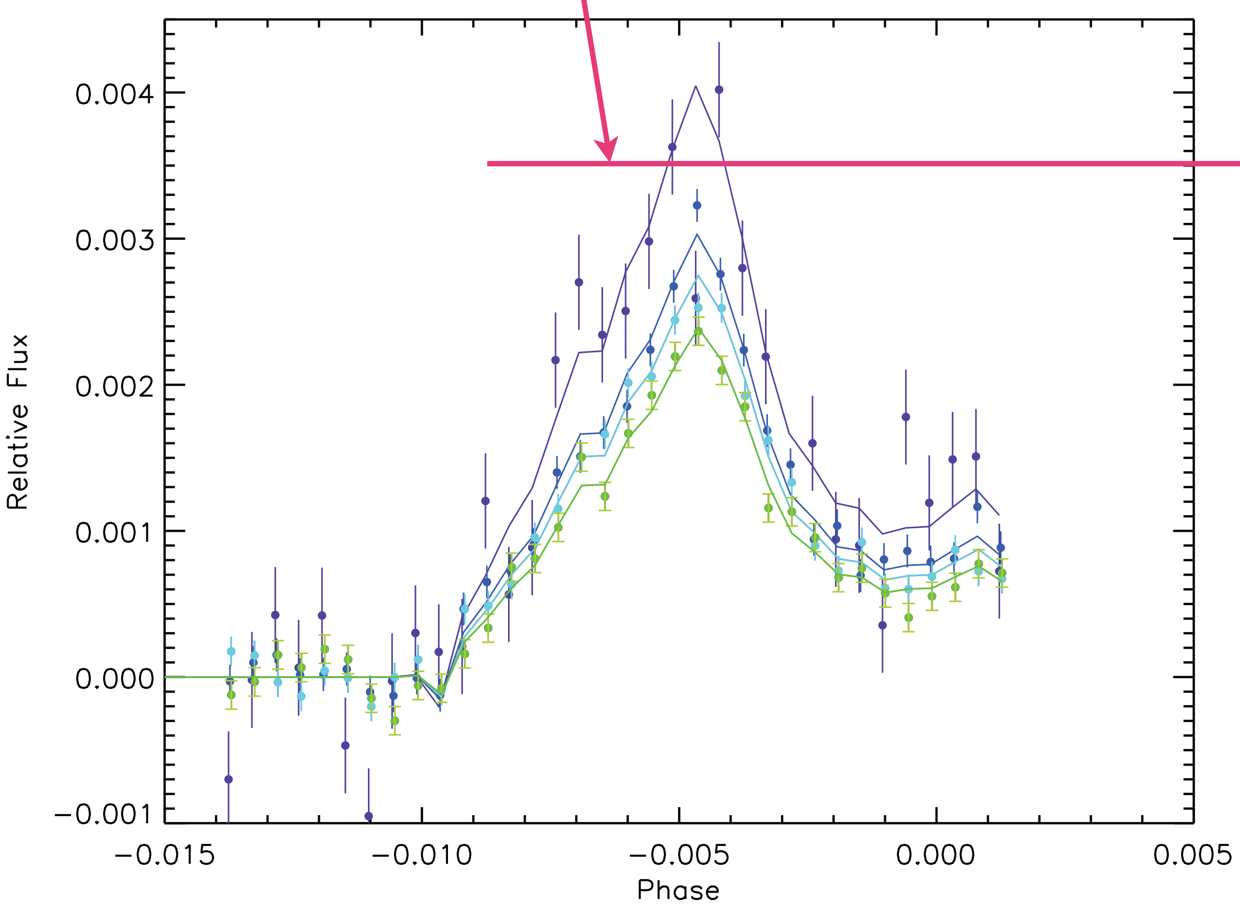


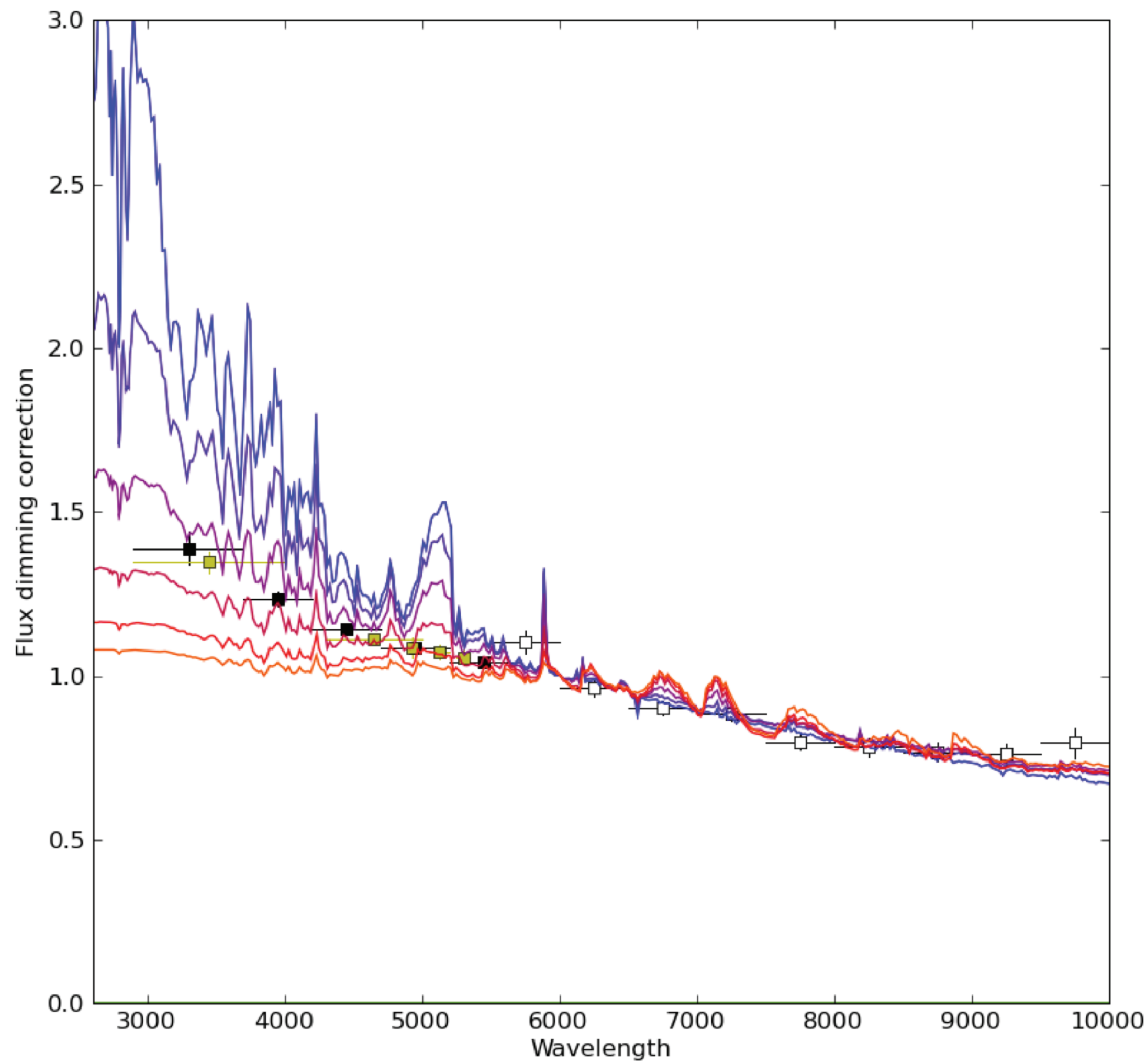
Estimate spectrum/temperature of spots from occulted spots

Accounting for spots in transmission spectra

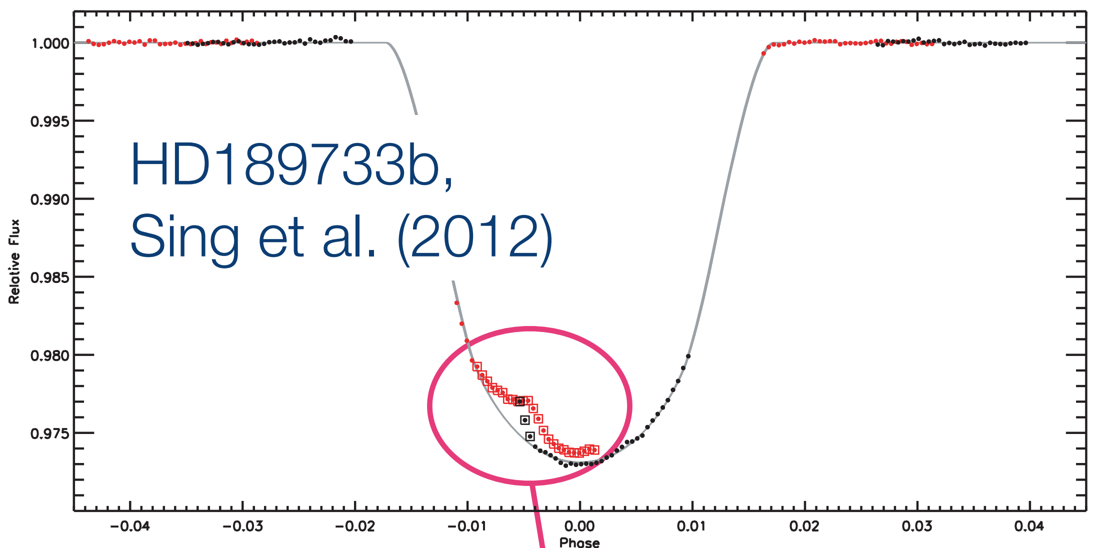


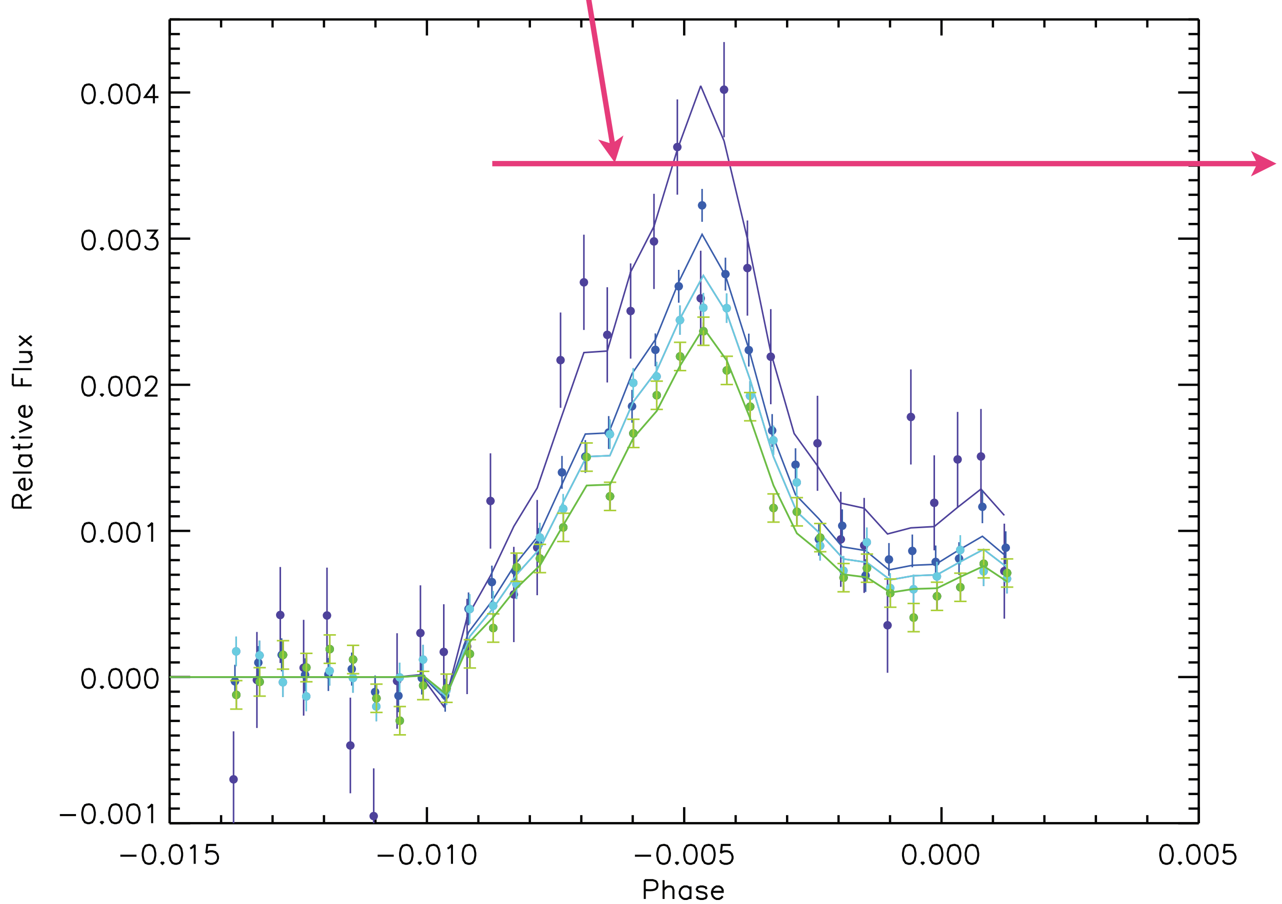
Estimate spectrum/temperature of spots from occulted spots



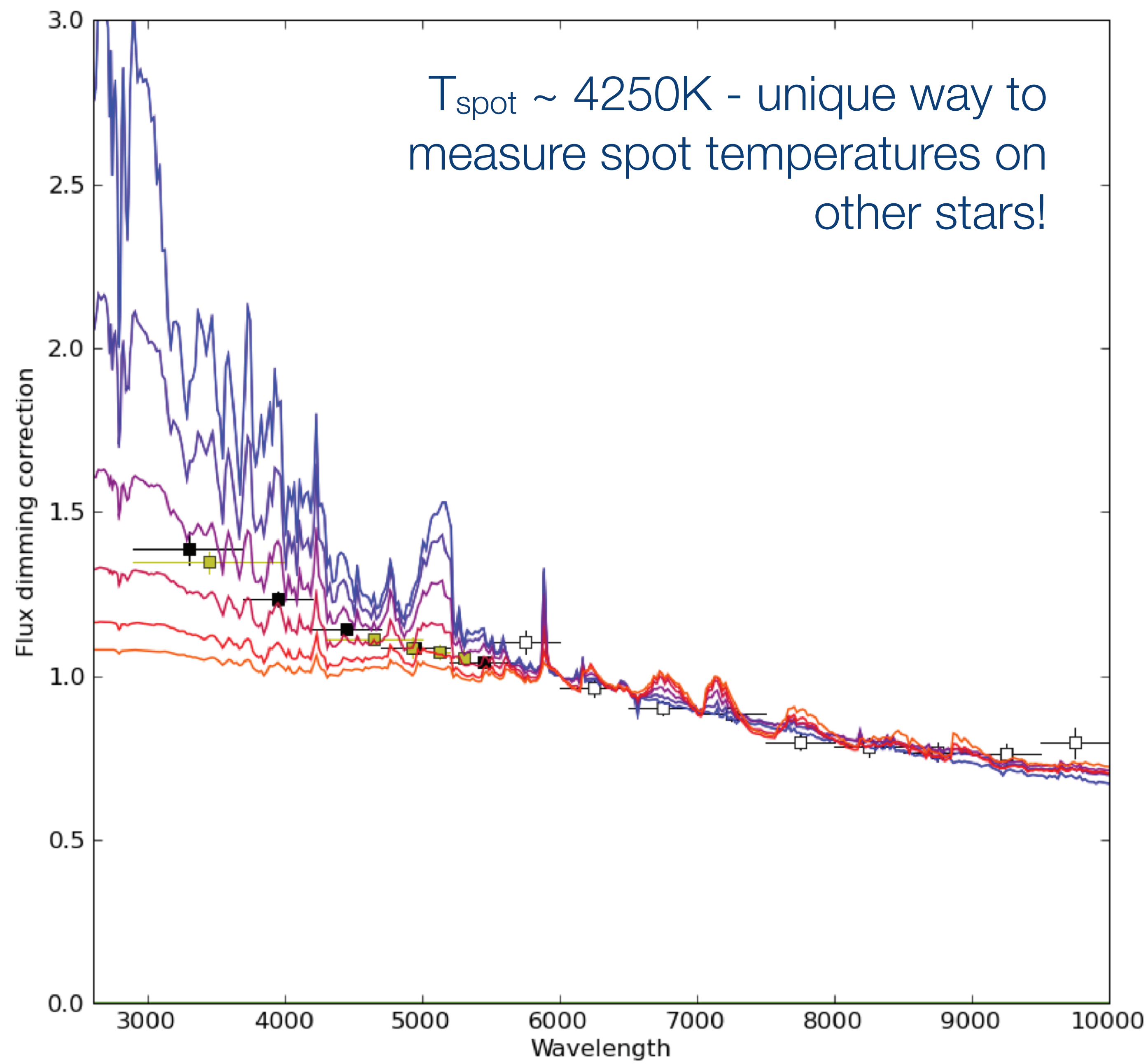


Accounting for spots in transmission spectra



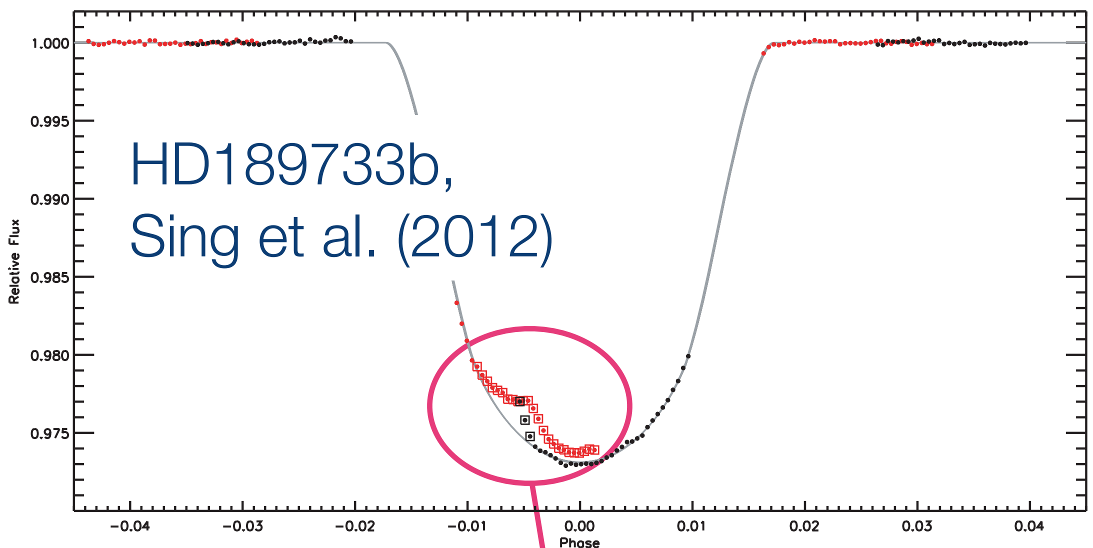


Estimate spectrum/temperature of spots from occulted spots

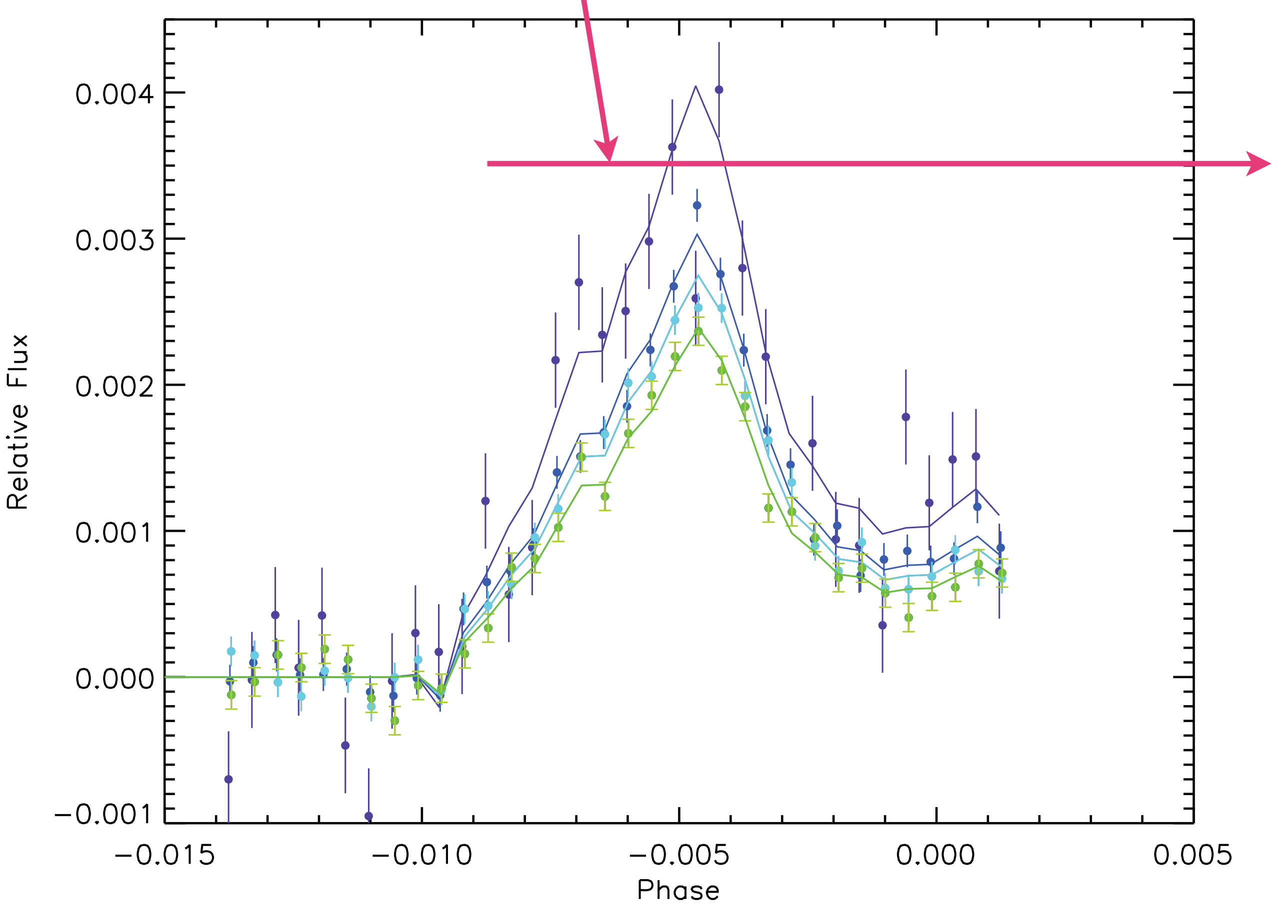


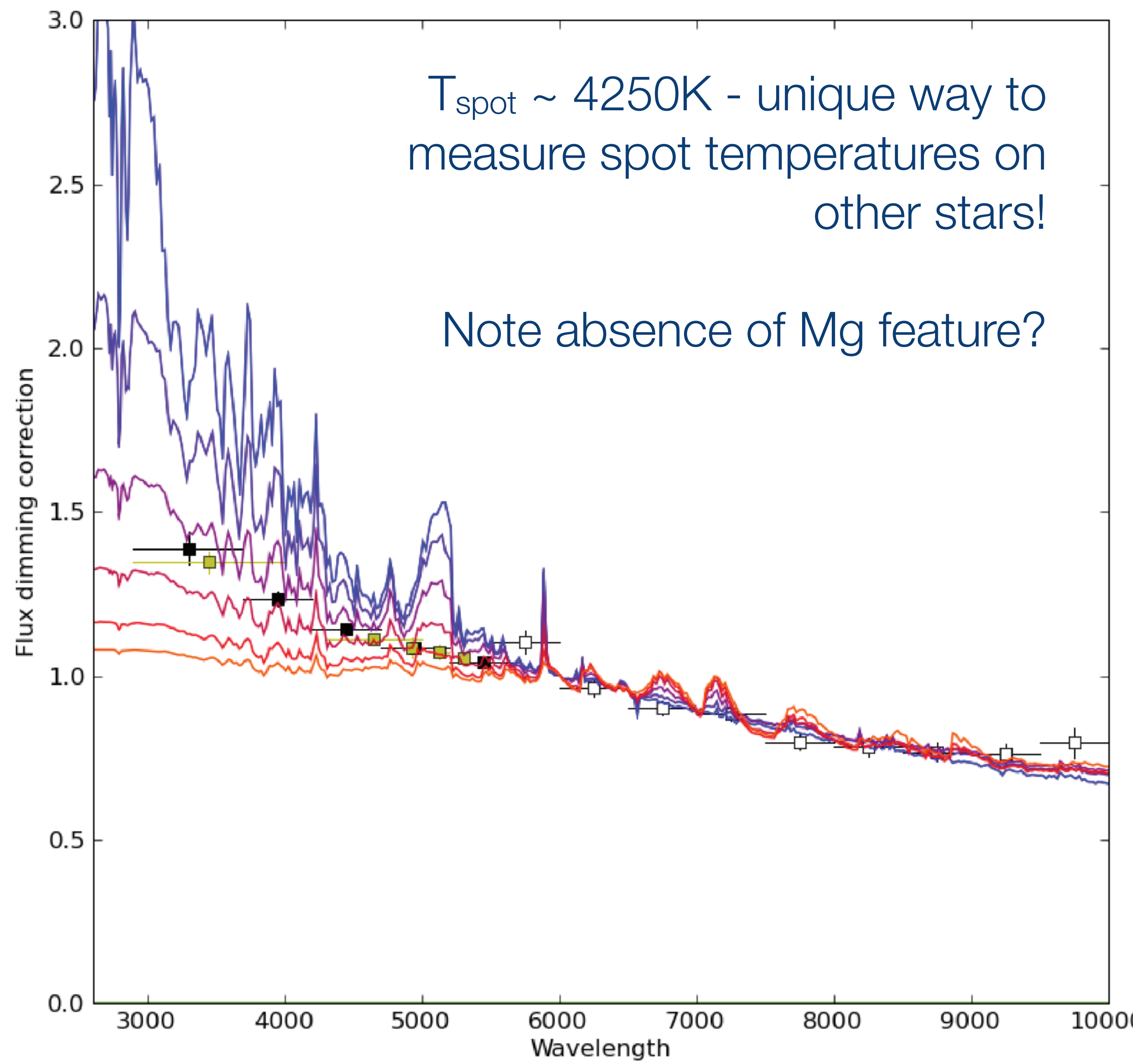
Accounting for spots in transmission spectra

Estimate spectrum/temperature of spots from occulted spots



HD189733b,
Sing et al. (2012)





T_{spot} ~ 4250K - unique way to measure spot temperatures on other stars!

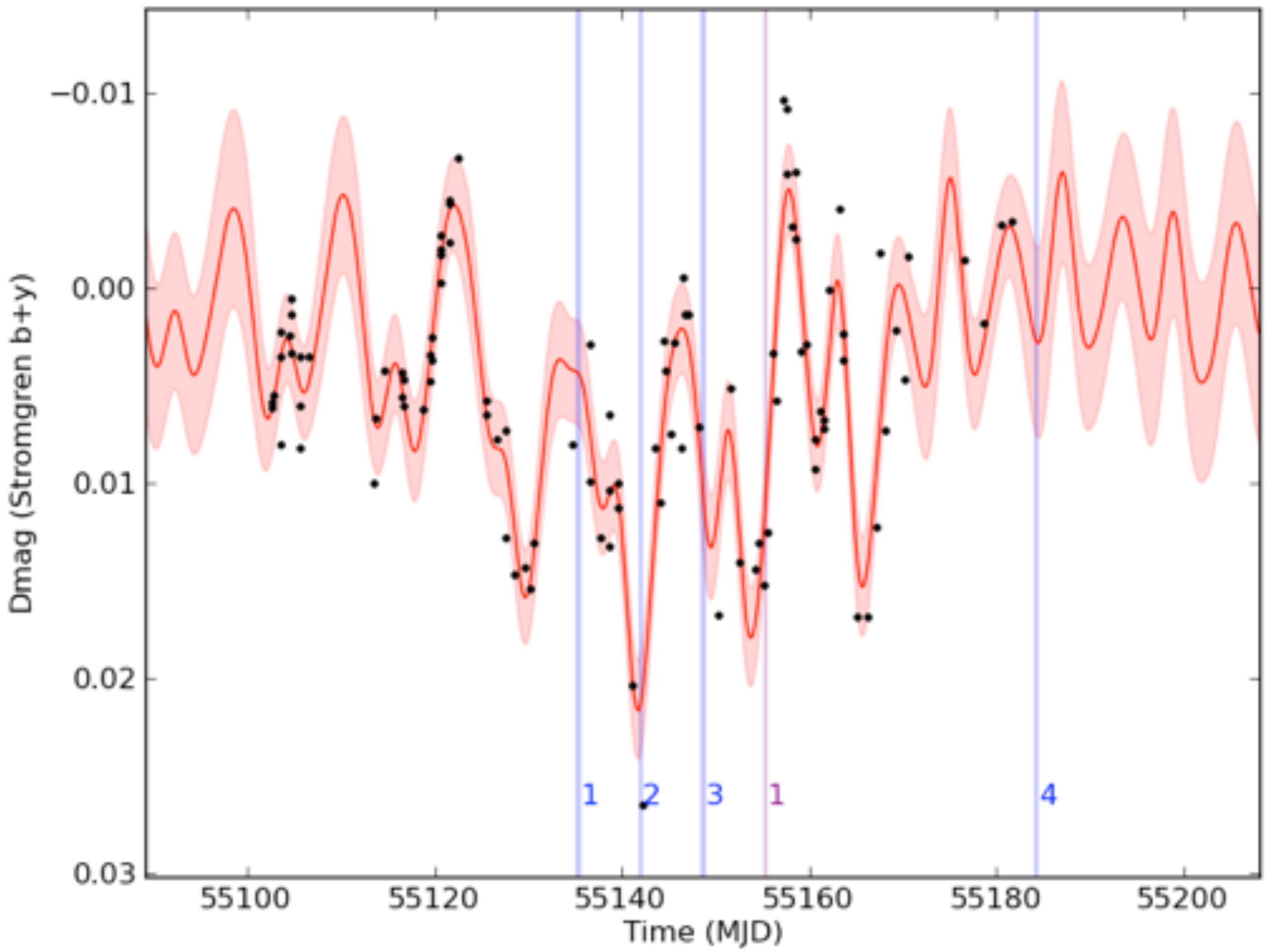
Note absence of Mg feature?

Accounting for spots in transmission spectra

Estimate spectrum/temperature of spots from occulted spots - only possible in visible

Estimate overall spot coverage from out-of-transit variability - only lower limit

HD189733 (Pont et al. 2013)



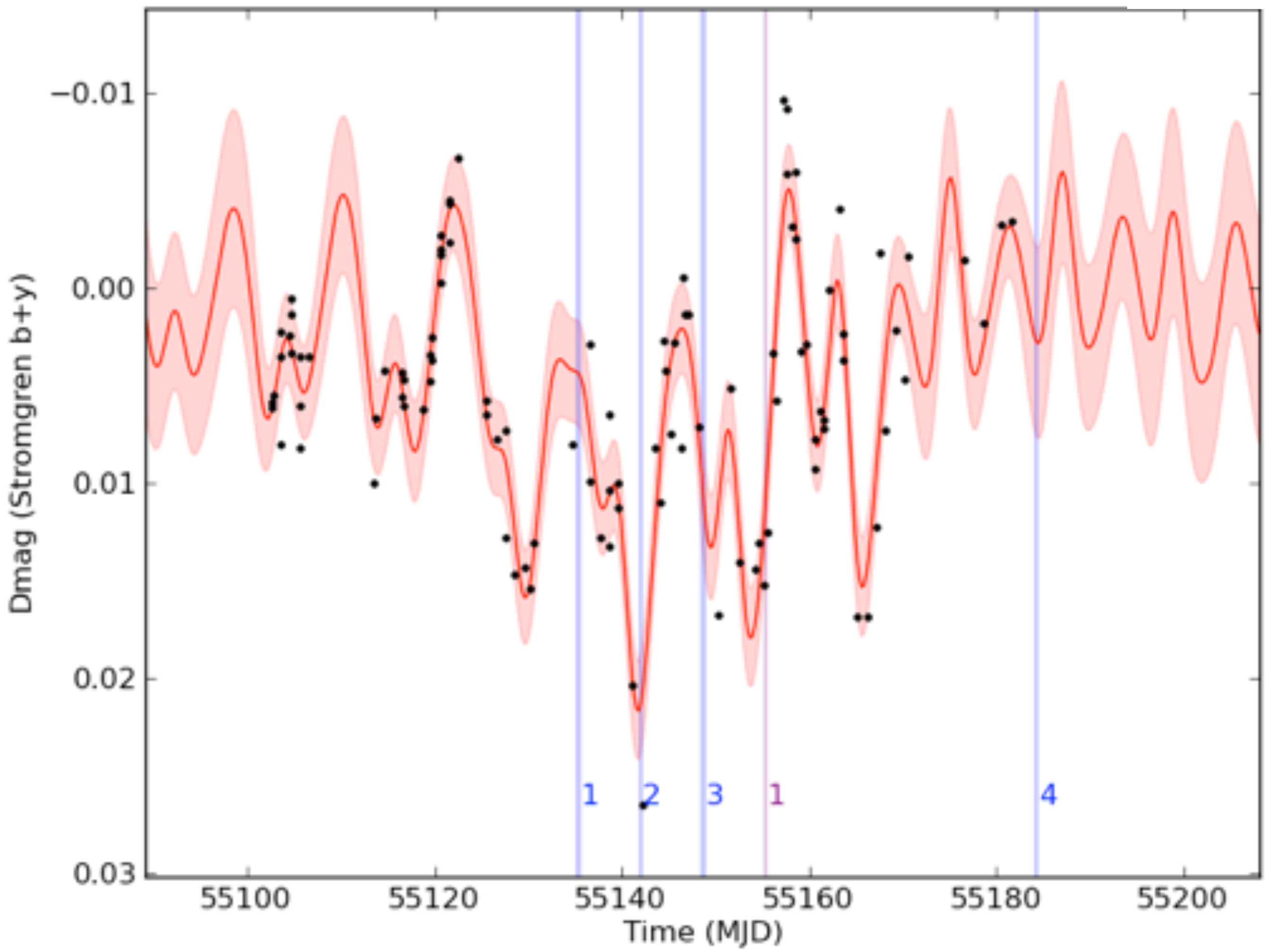
Accounting for spots in transmission spectra

Estimate spectrum/temperature of spots from occulted spots - only possible in visible

Estimate overall spot coverage from out-of-transit variability - only lower limit

Estimate spot coverage of transit chord from rate of occulted spots - only catch the big ones

HD189733 (Pont et al. 2013)



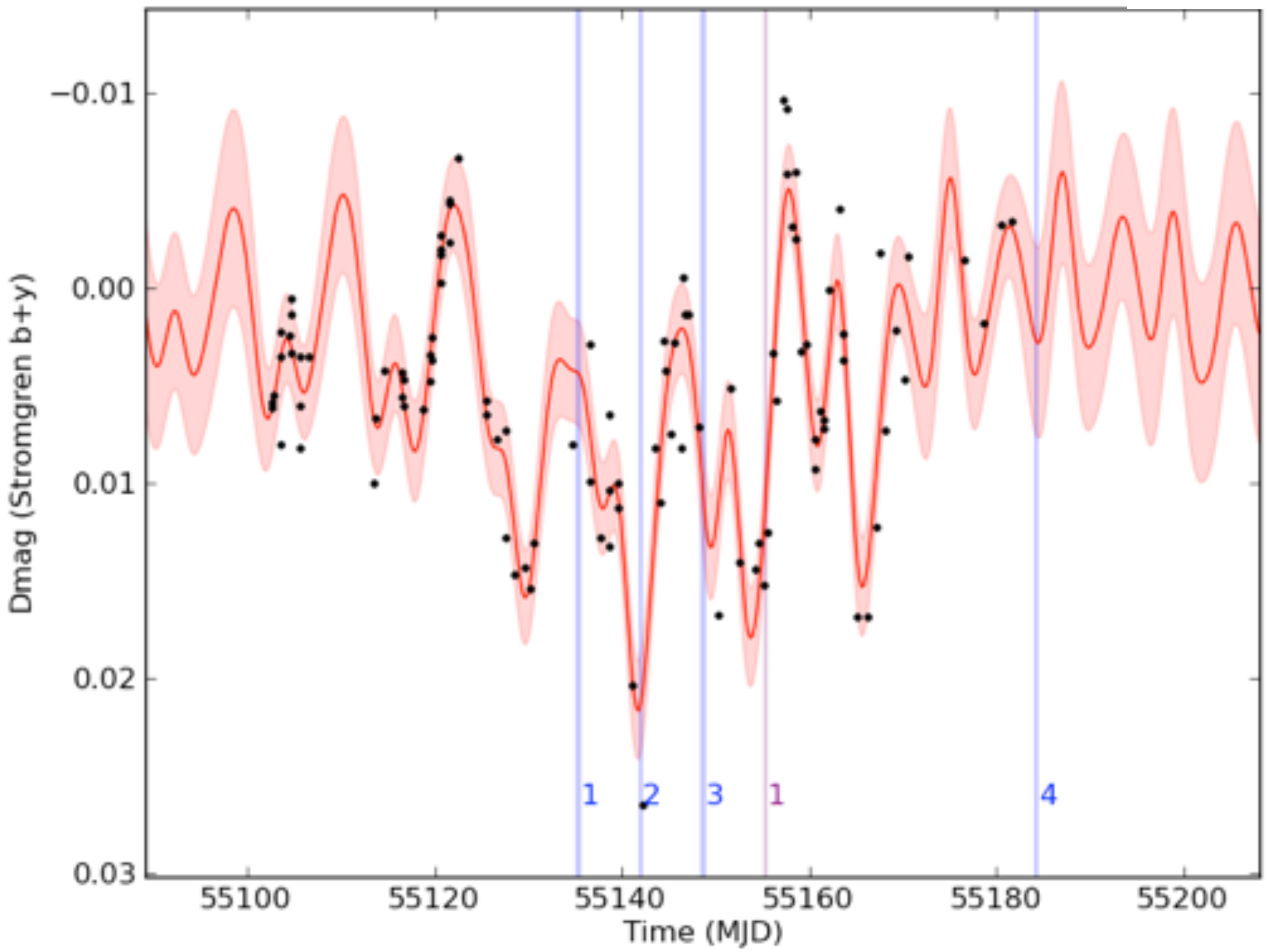
Accounting for spots in transmission spectra

Estimate spectrum/temperature of spots from occulted spots - only possible in visible

Estimate overall spot coverage from out-of-transit variability - only lower limit

Estimate spot coverage of transit chord from rate of occulted spots - only catch the big ones

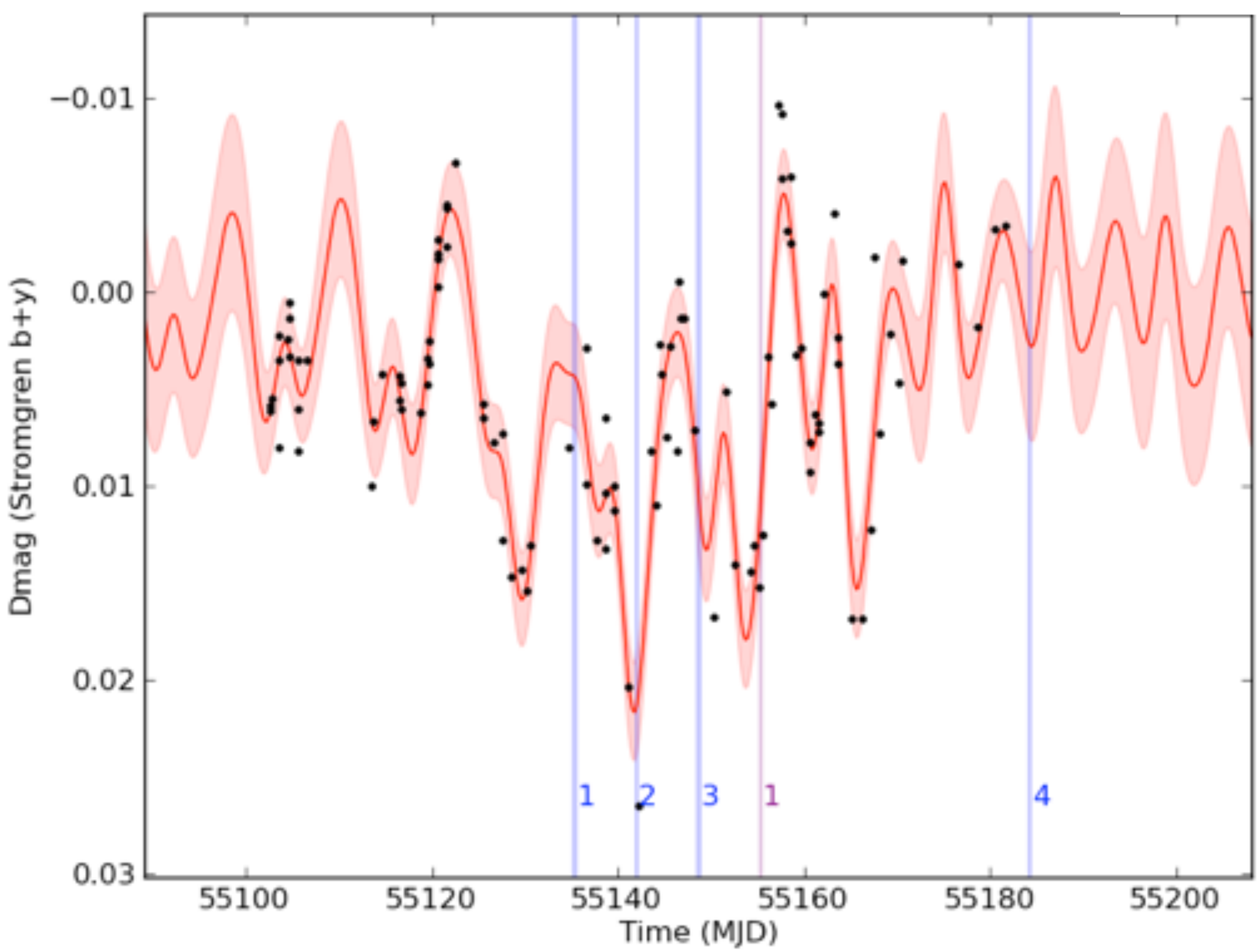
HD189733 (Pont et al. 2013)



In best cases, can estimate uncertainties due to spots, but not really correct for them

Accounting for spots in transmission spectra

HD189733 (Pont et al. 2013)



Estimate spectrum/temperature of spots from occulted spots - only possible in visible

Estimate overall spot coverage from out-of-transit variability - only lower limit

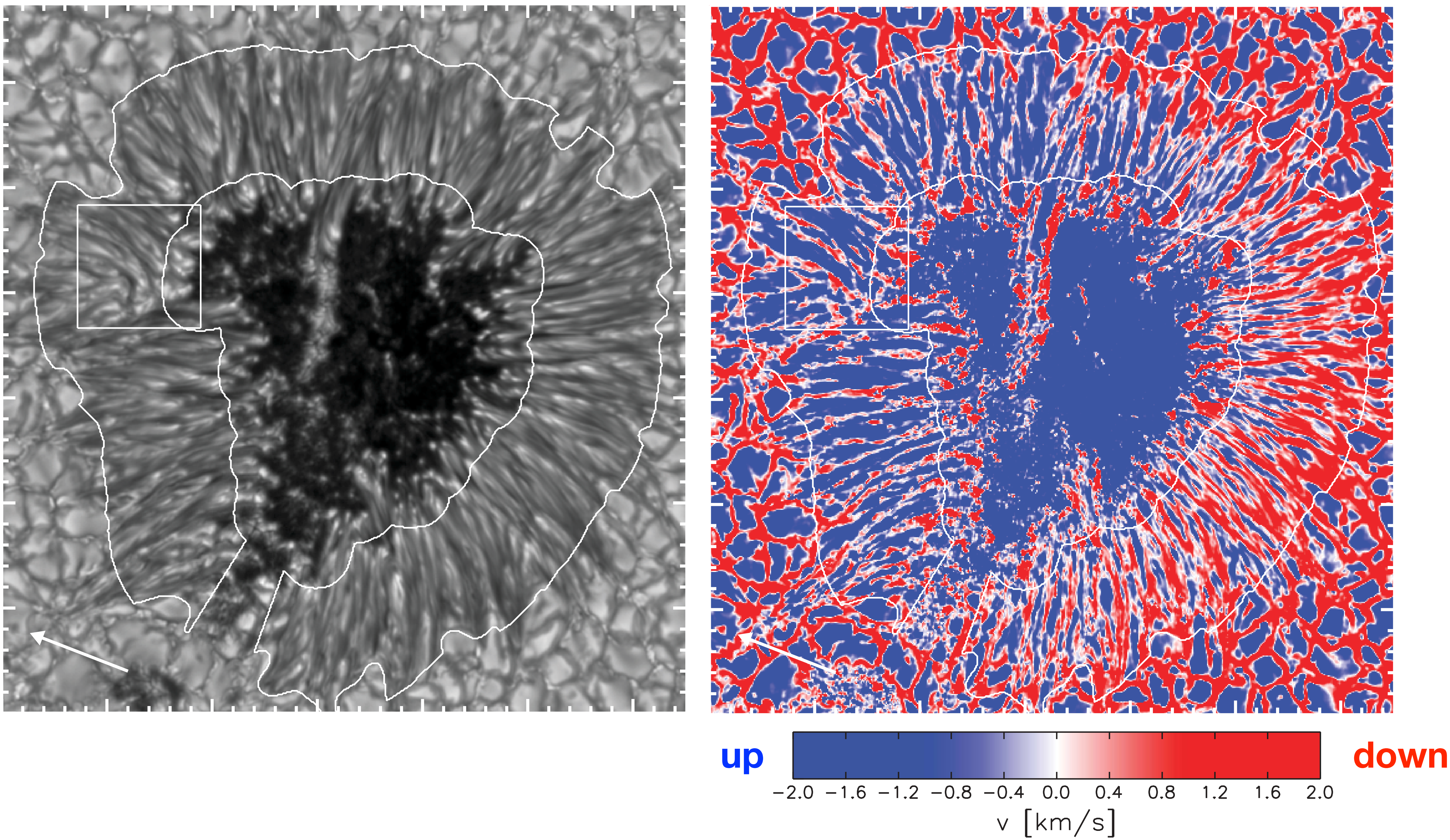
Estimate spot coverage of transit chord from rate of occulted spots - only catch the big ones

In best cases, can estimate uncertainties due to spots, but not really correct for them

Getting entire spectrum in one go helps! cf. EChO project

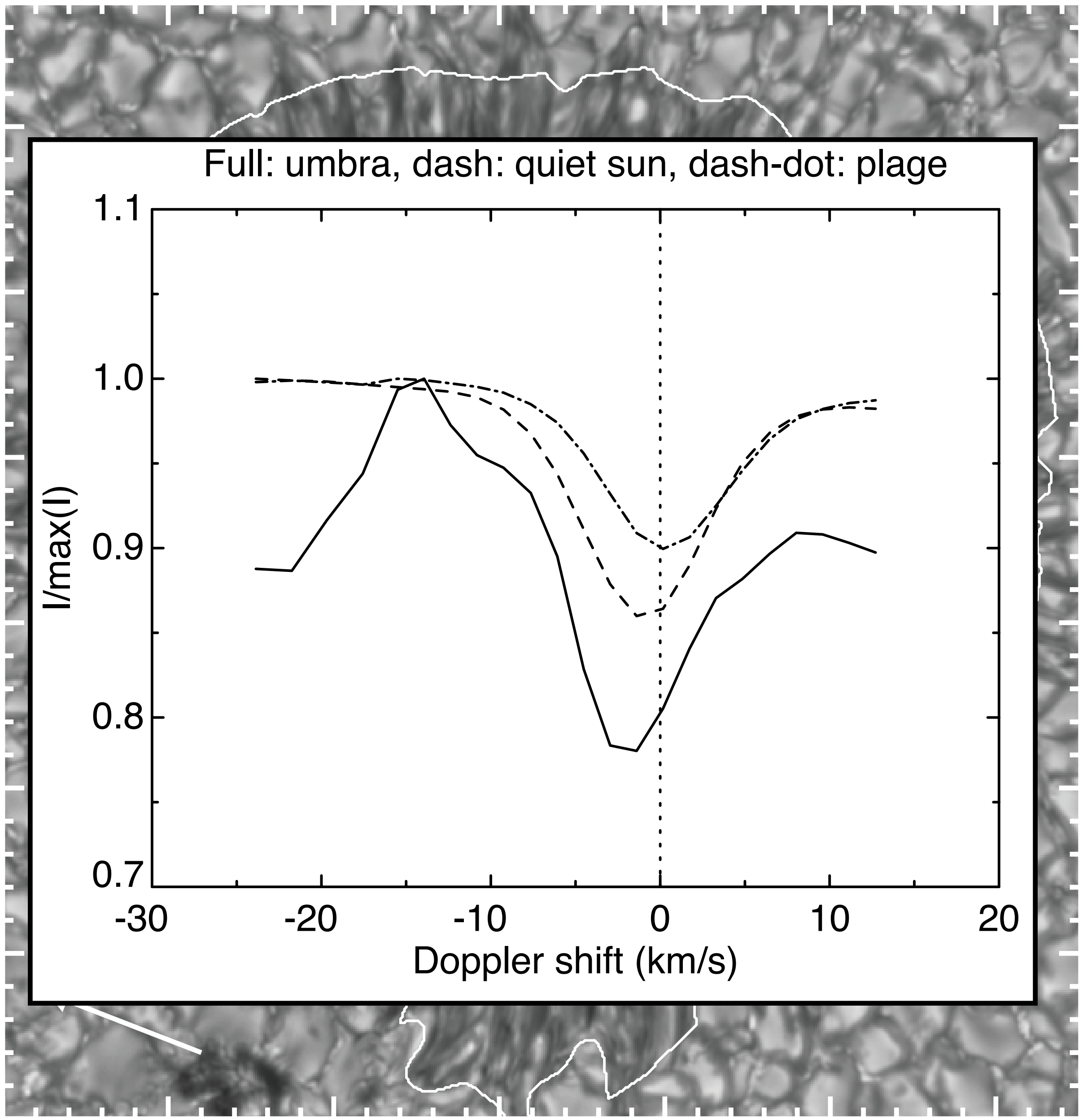
Spectroscopic effects of star spots
impact on RV measurements

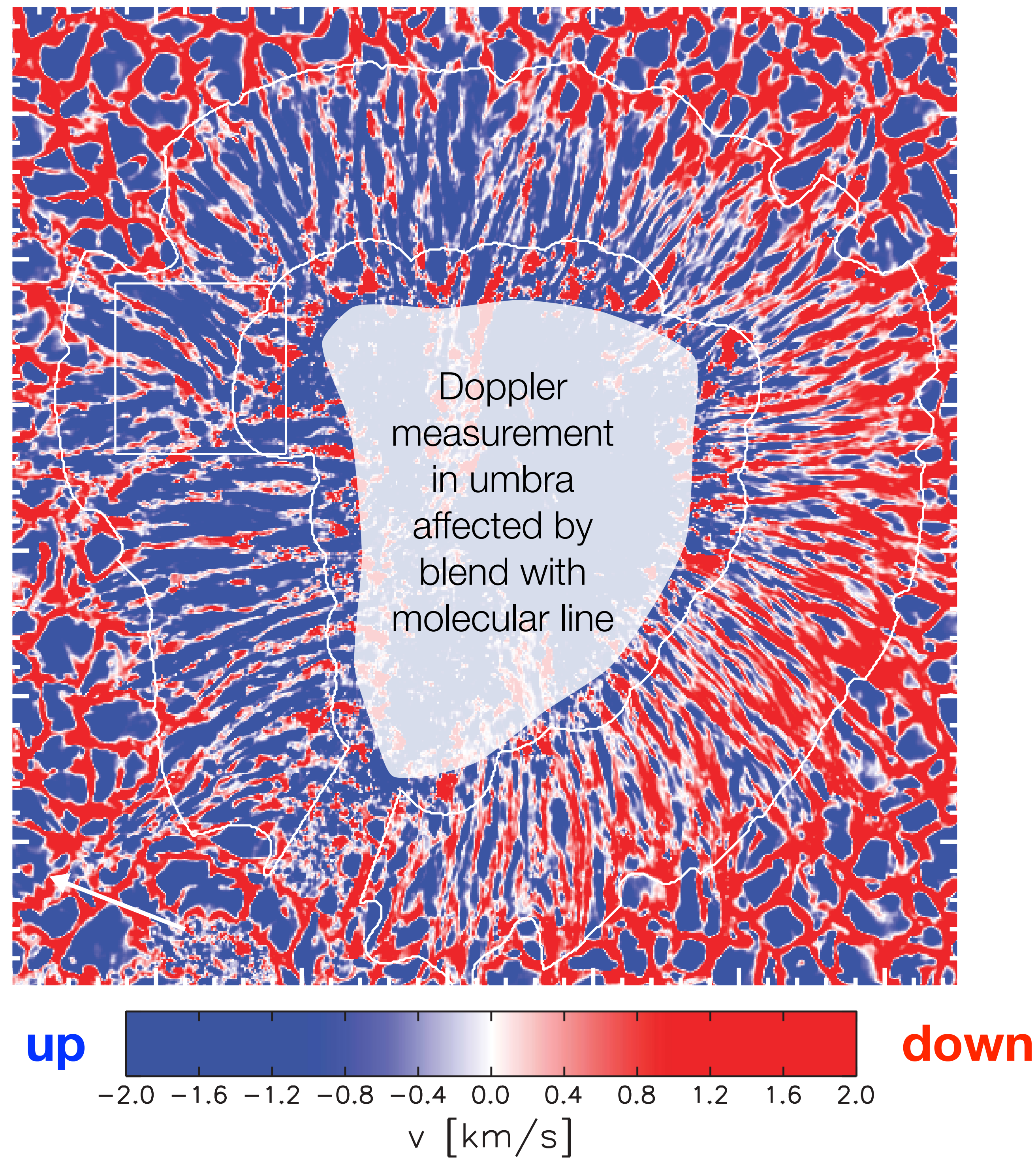
Scharmer et al., Science, 2011



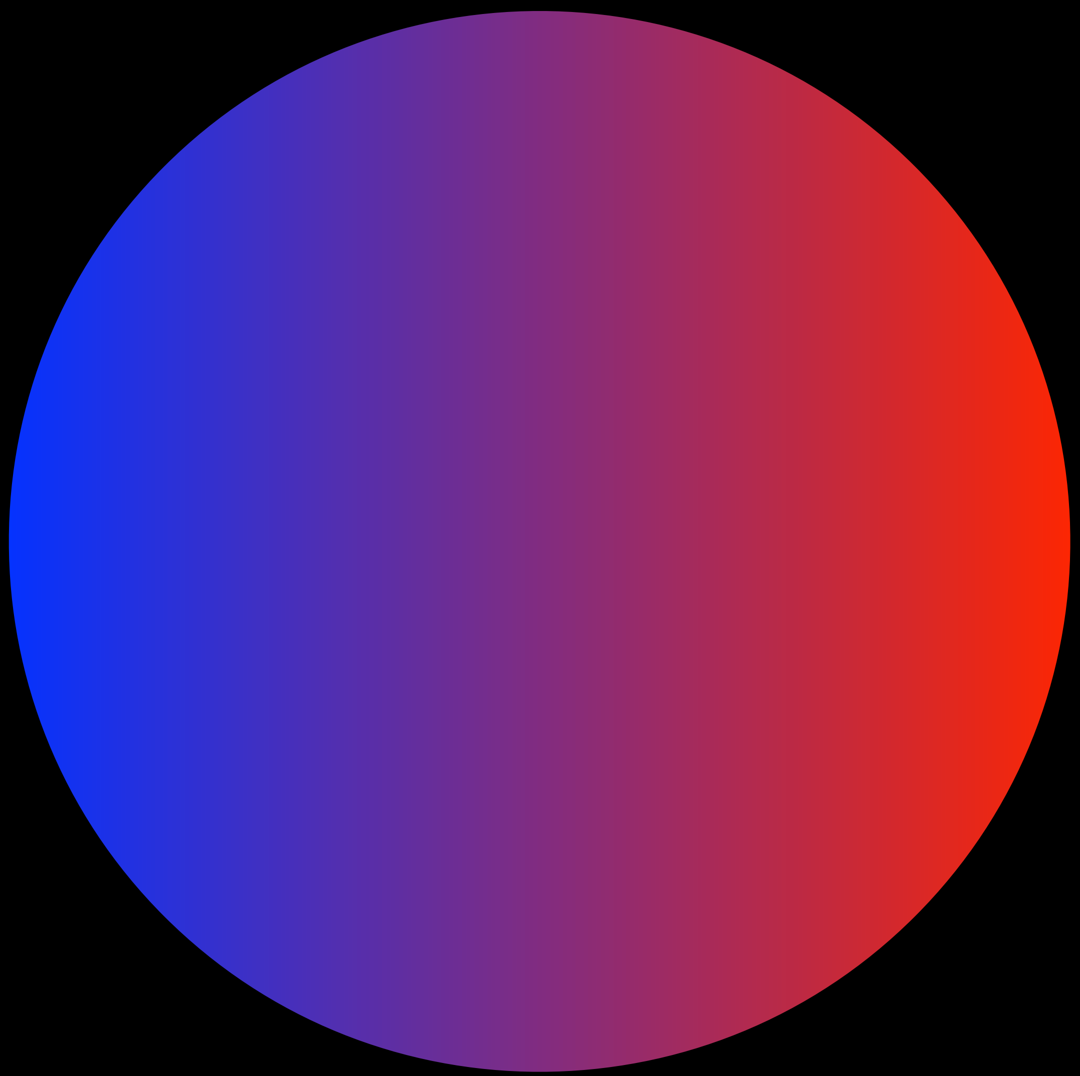
Spectroscopic effects of star spots
impact on RV measurements

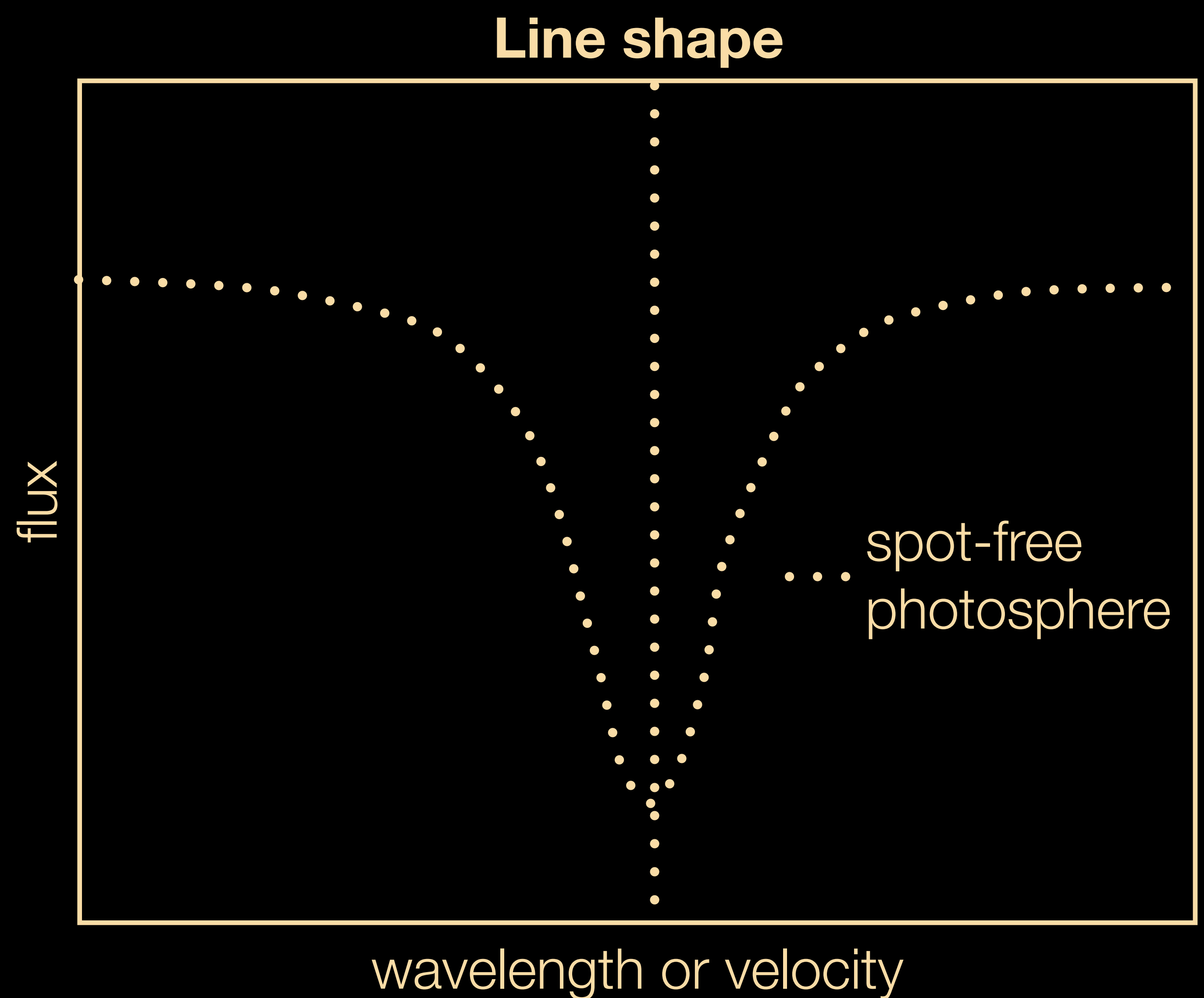
Scharmer et al., Science, 2011



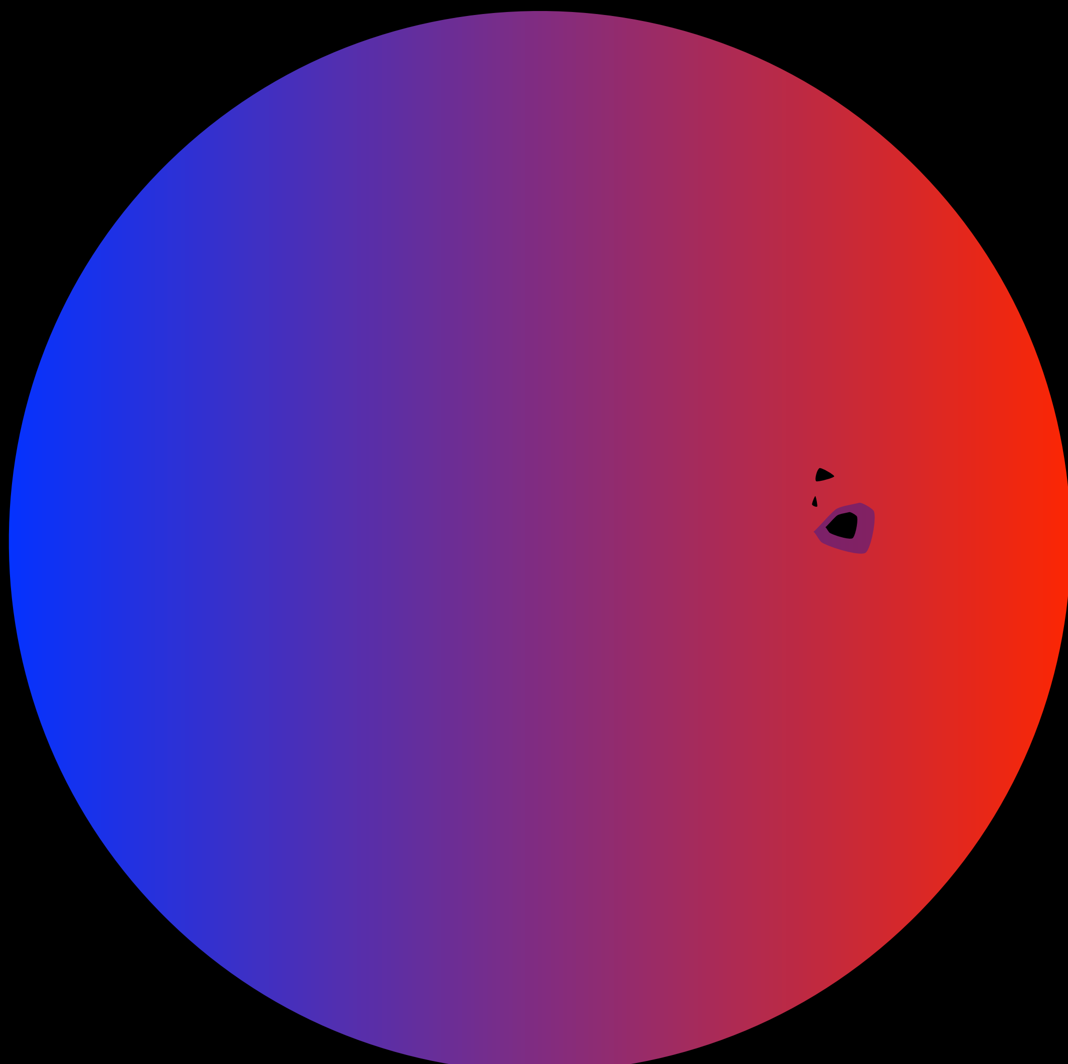


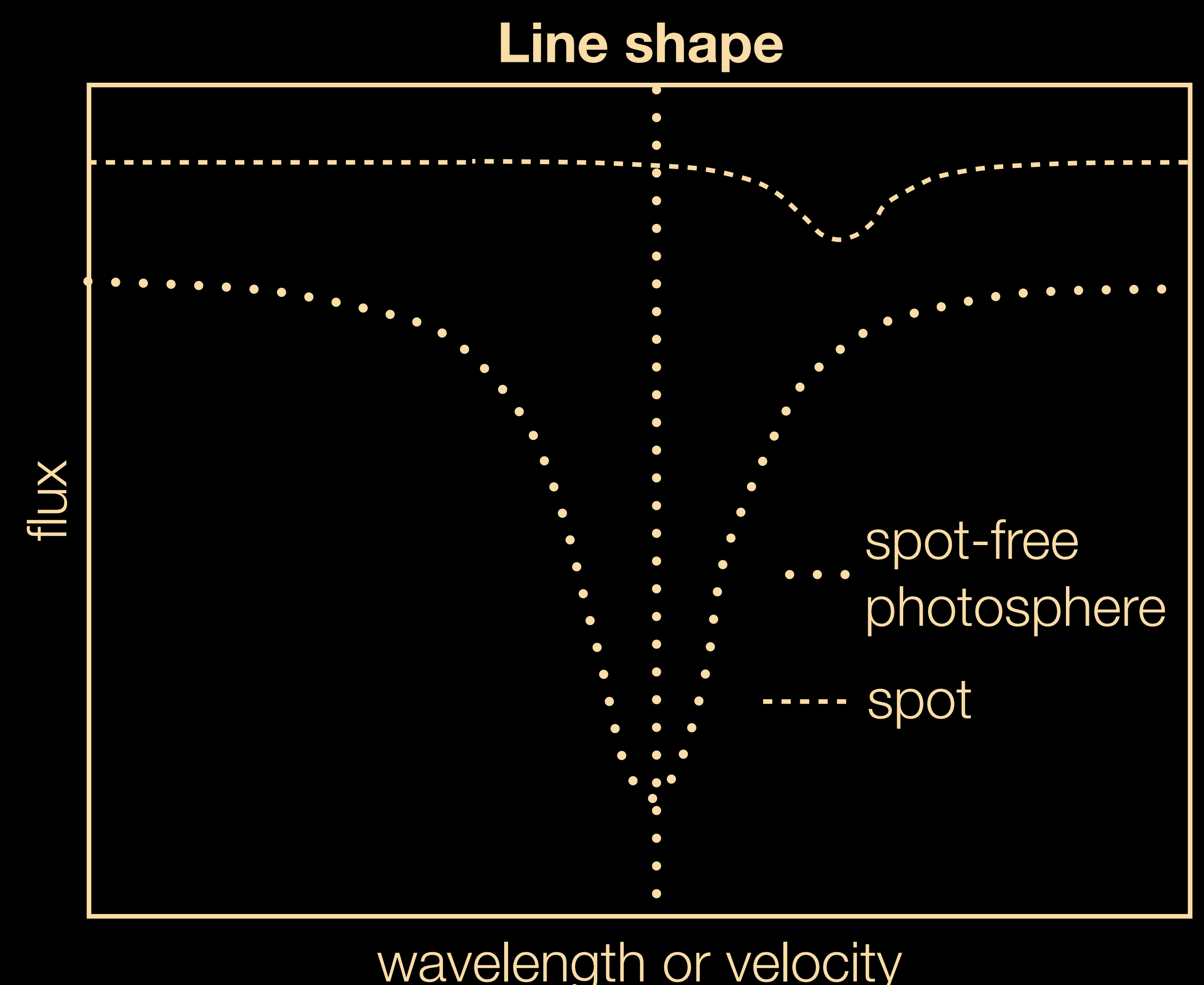
RV effects of activity - 1: distortion of rotation profile



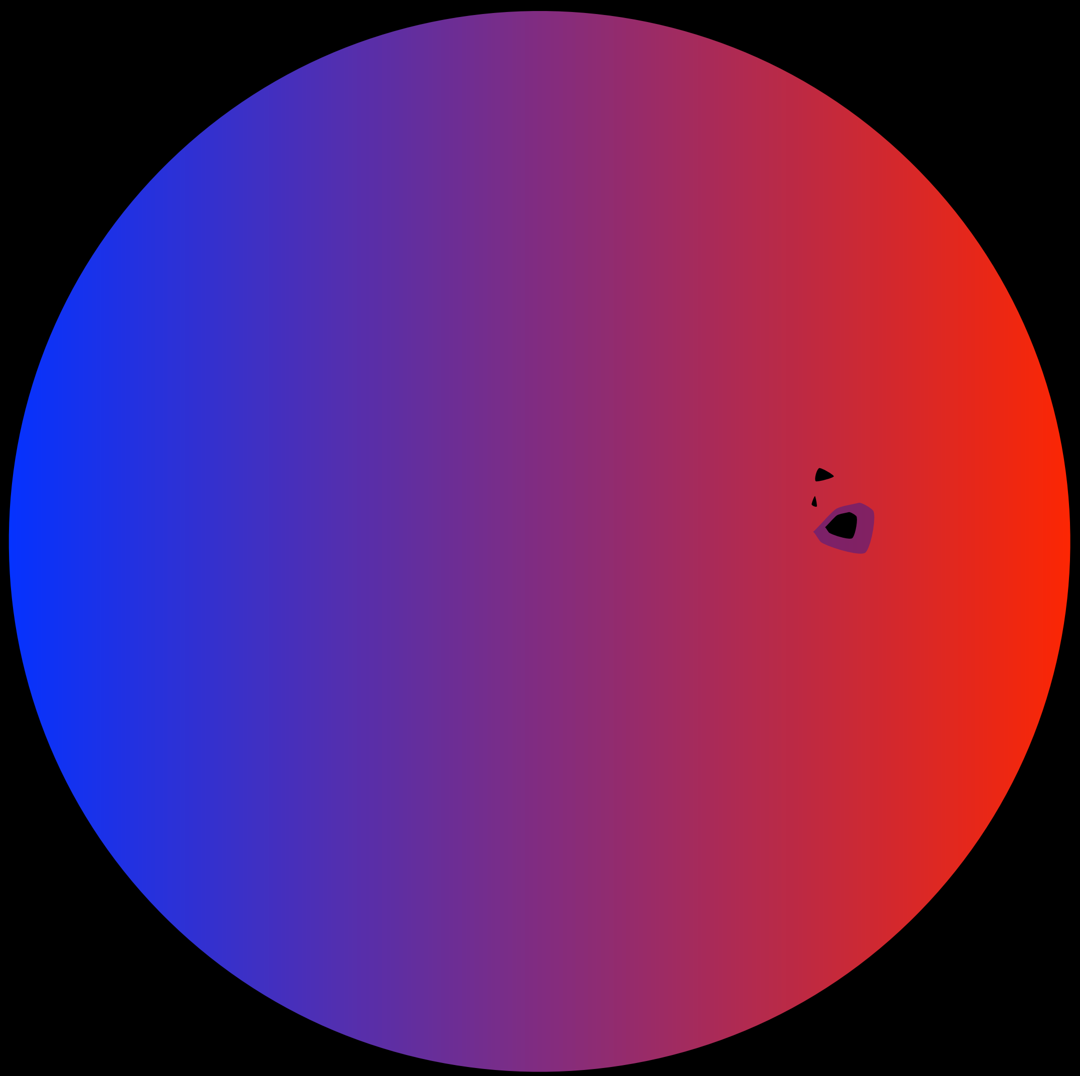


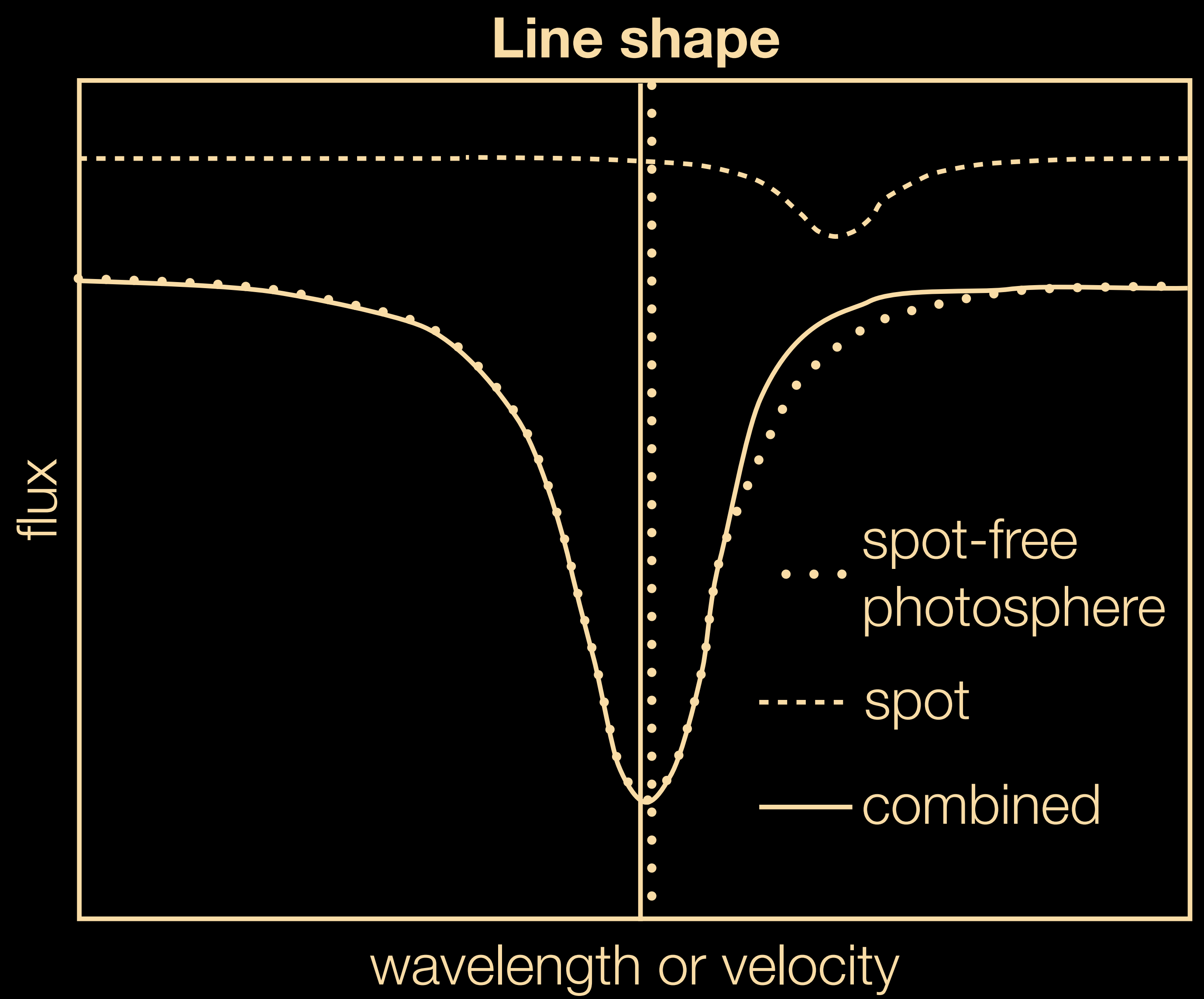
RV effects of activity - 1:
distortion of rotation profile



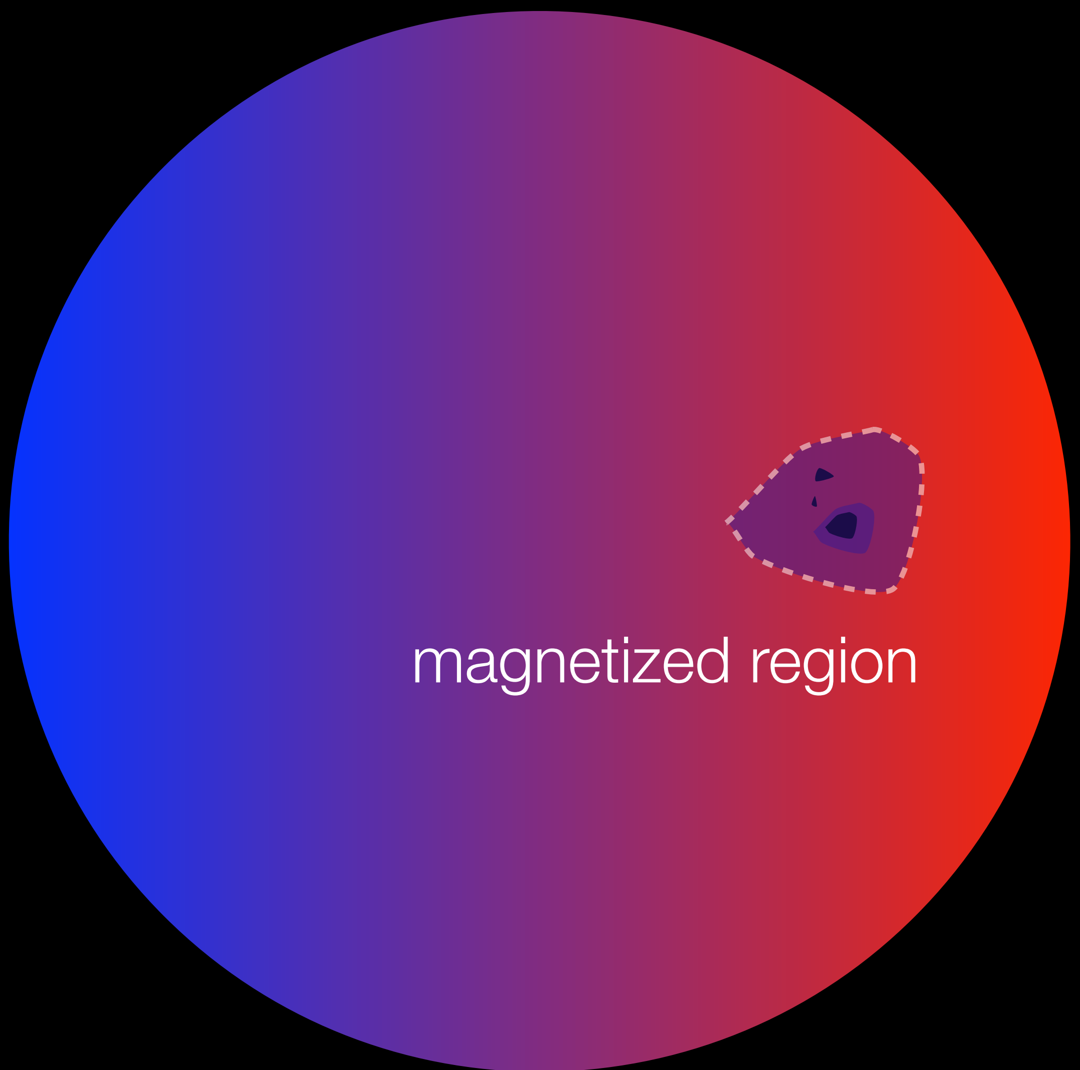


RV effects of activity - 1: distortion of rotation profile





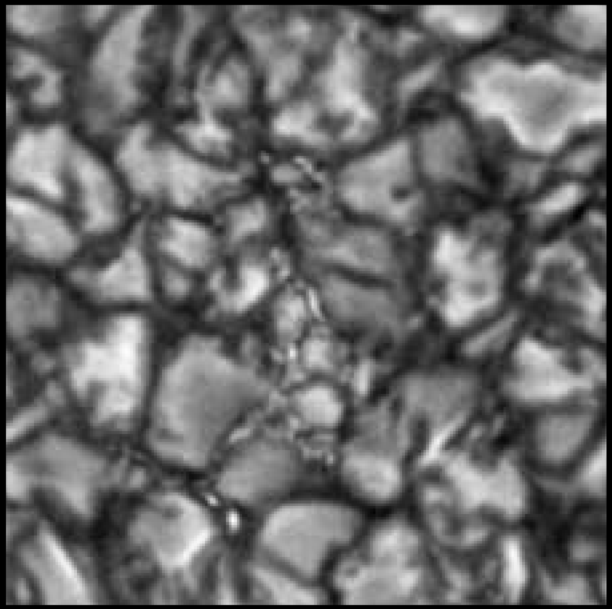
RV effects of activity - 2: convective blueshift suppression



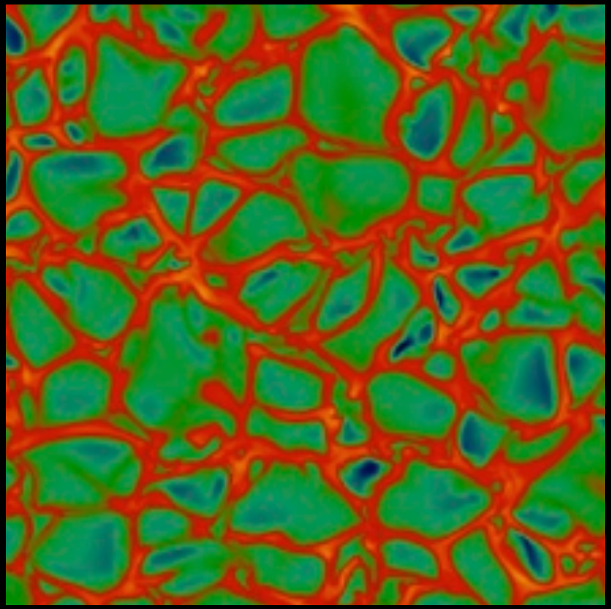
Convection is partially suppressed in regions where surface magnetic field is large

Why does this affect RVs?

Spectral line asymmetries in “normal” photosphere



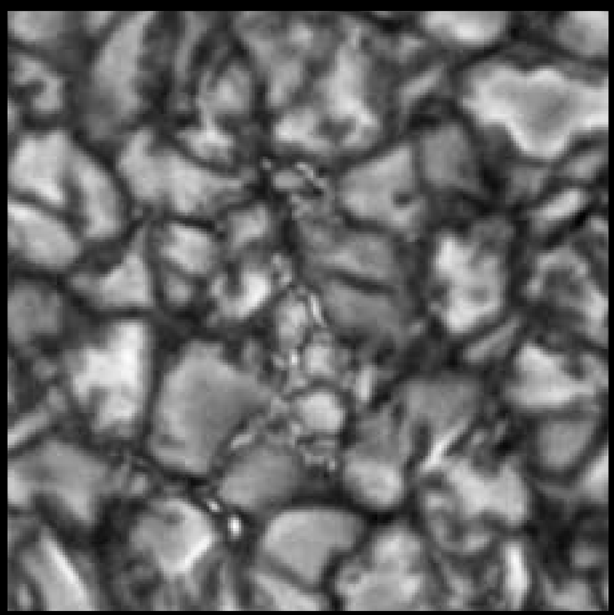
observed intensity
(MESA, Dunn telescope)



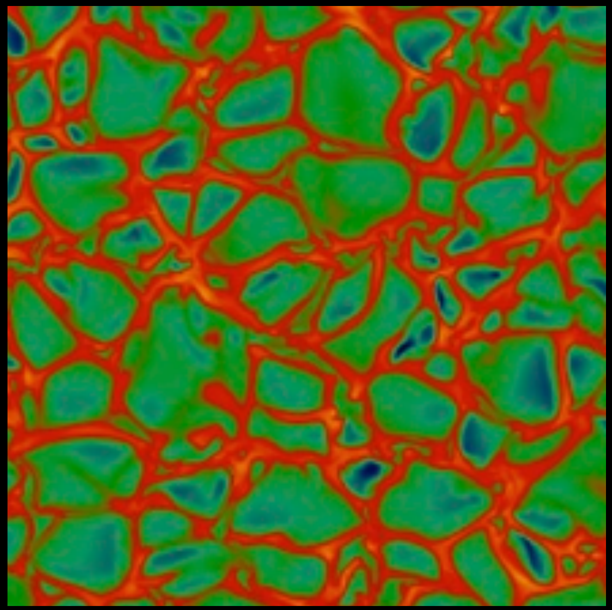
simulated
LOS velocity
(Cegla et al. 2013)

up (towards us)
down (away from us)

Spectral line asymmetries in “normal” photosphere

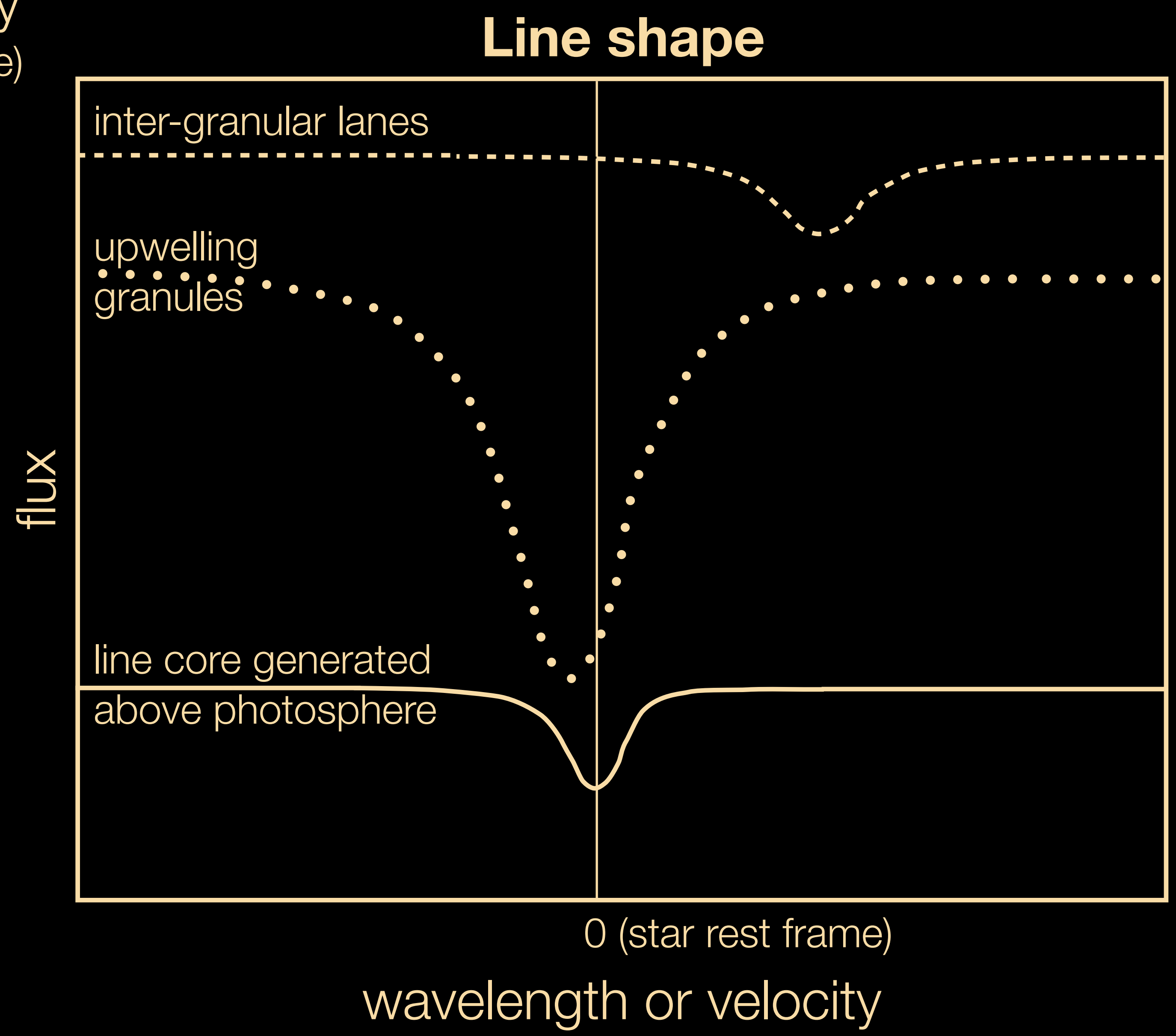


observed intensity
(MESA, Dunn telescope)

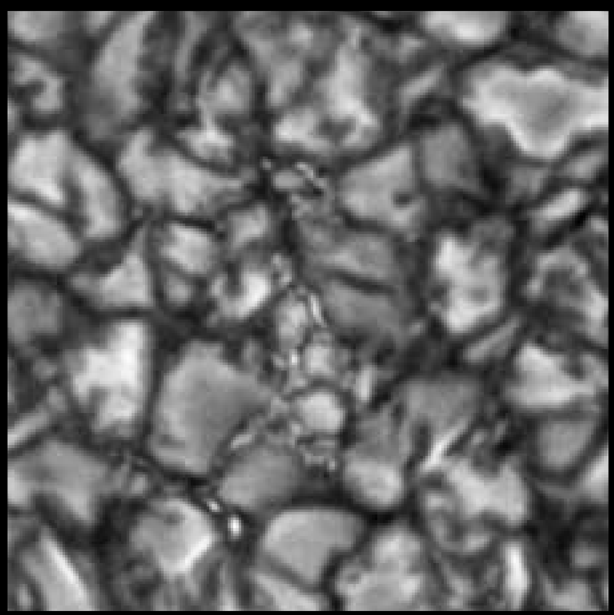


simulated
LOS velocity
(Cegla et al. 2013)

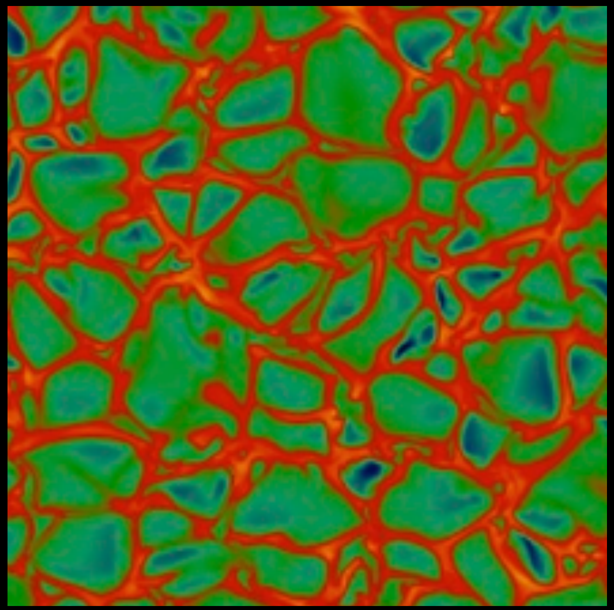
up (towards us)
down (away from us)



Spectral line asymmetries in “normal” photosphere

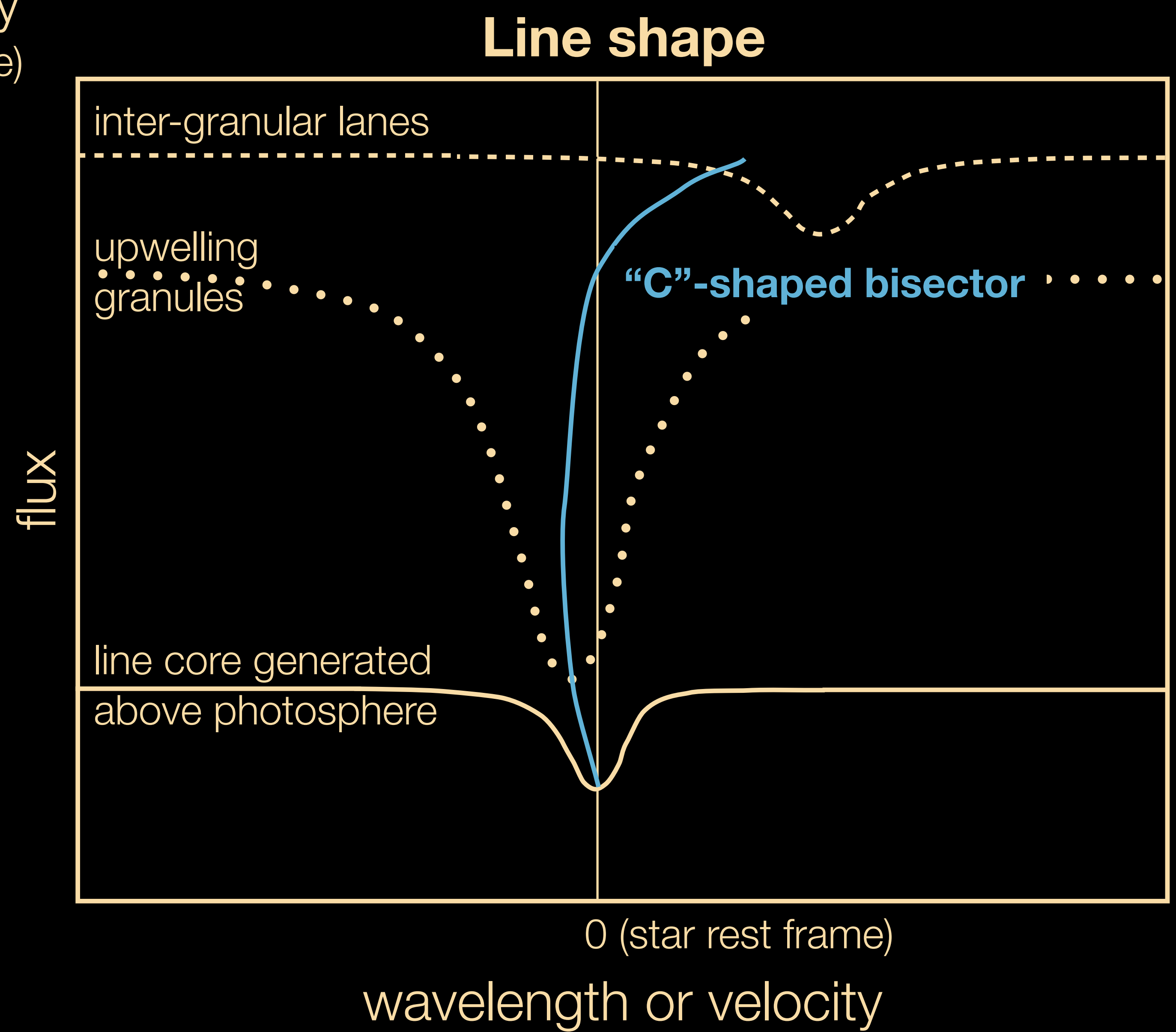


observed intensity
(MESA, Dunn telescope)

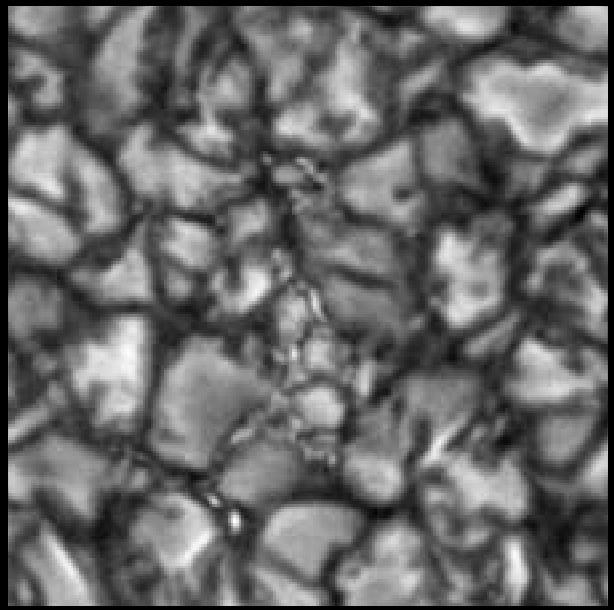


simulated
LOS velocity
(Cegla et al. 2013)

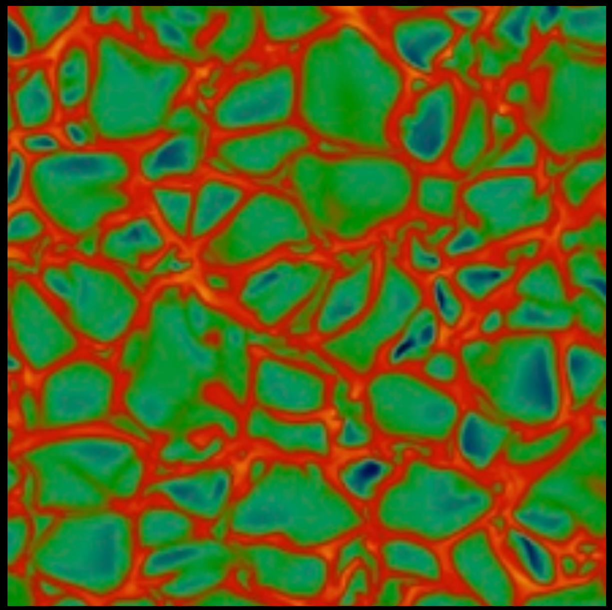
up (towards us)
down (away from us)



Spectral line asymmetries in "normal" photosphere

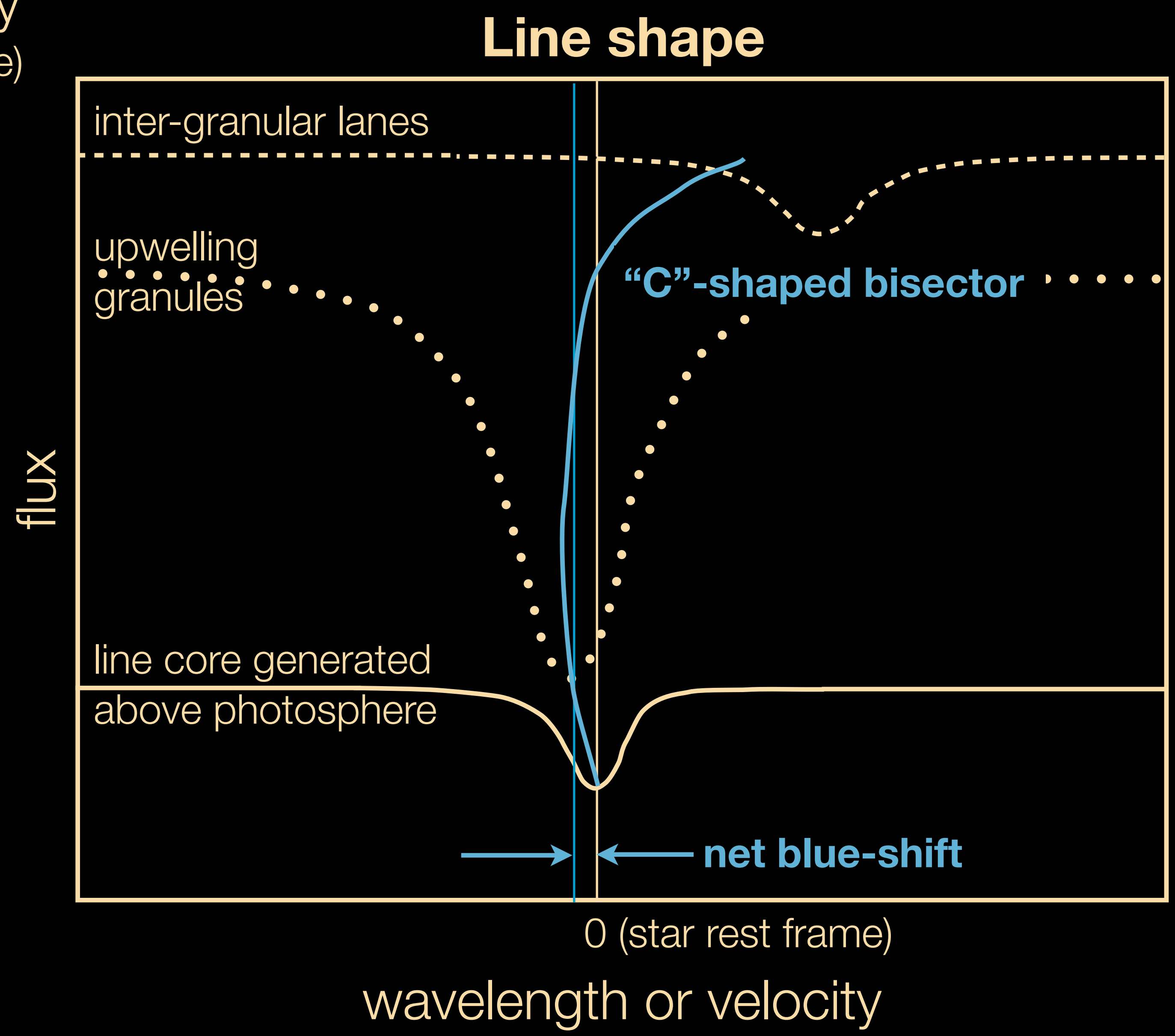


observed intensity
(MESA, Dunn telescope)

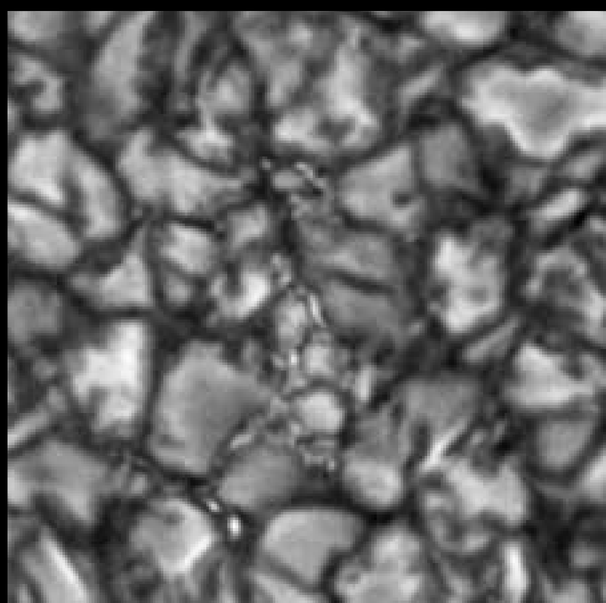


simulated
LOS velocity
(Cegla et al. 2013)

up (towards us)
down (away from us)



Spectral line asymmetries in “normal” photosphere

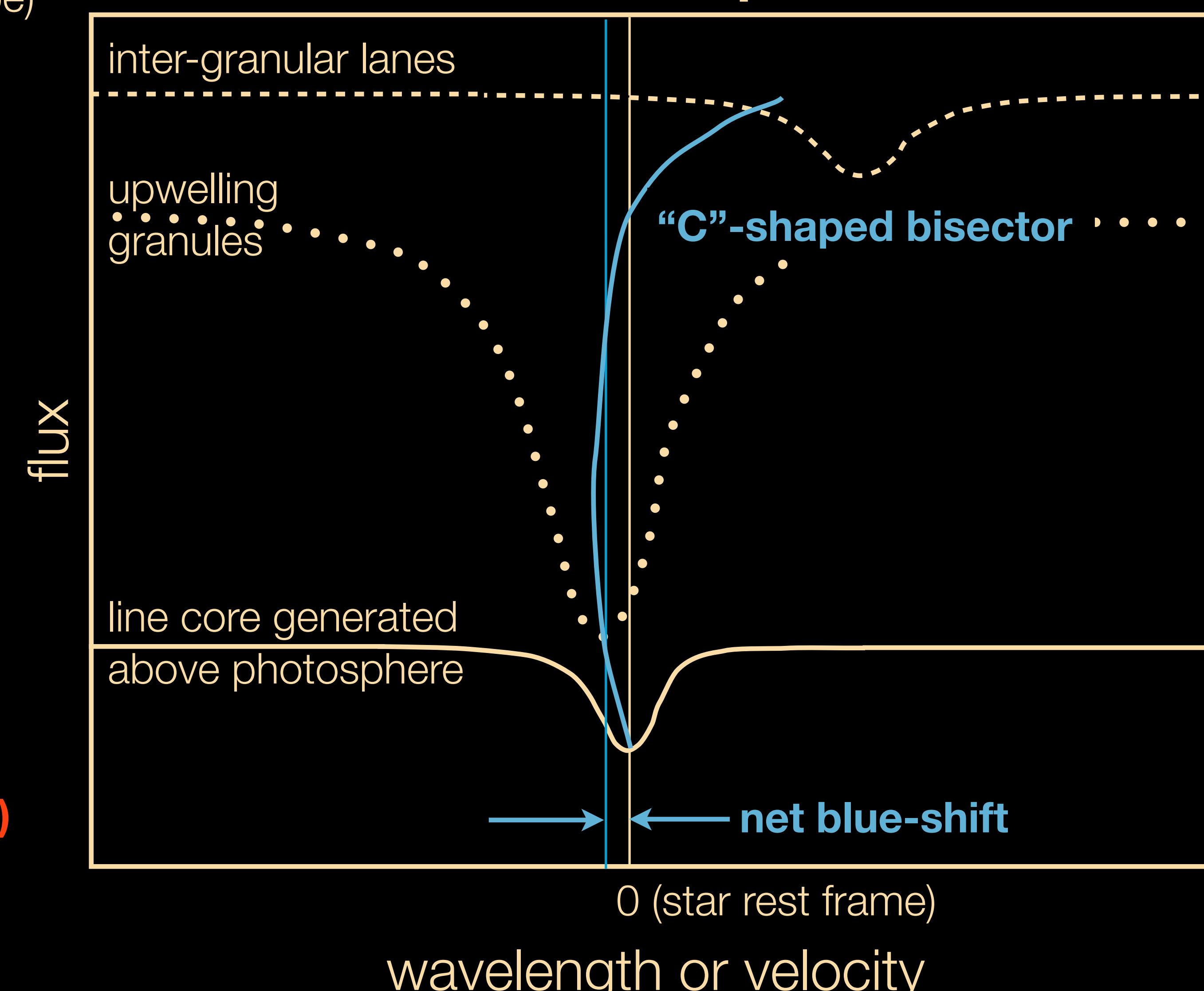


observed intensity
(MESA, Dunn telescope)

simulated
LOS velocity
(Cegla et al. 2013)

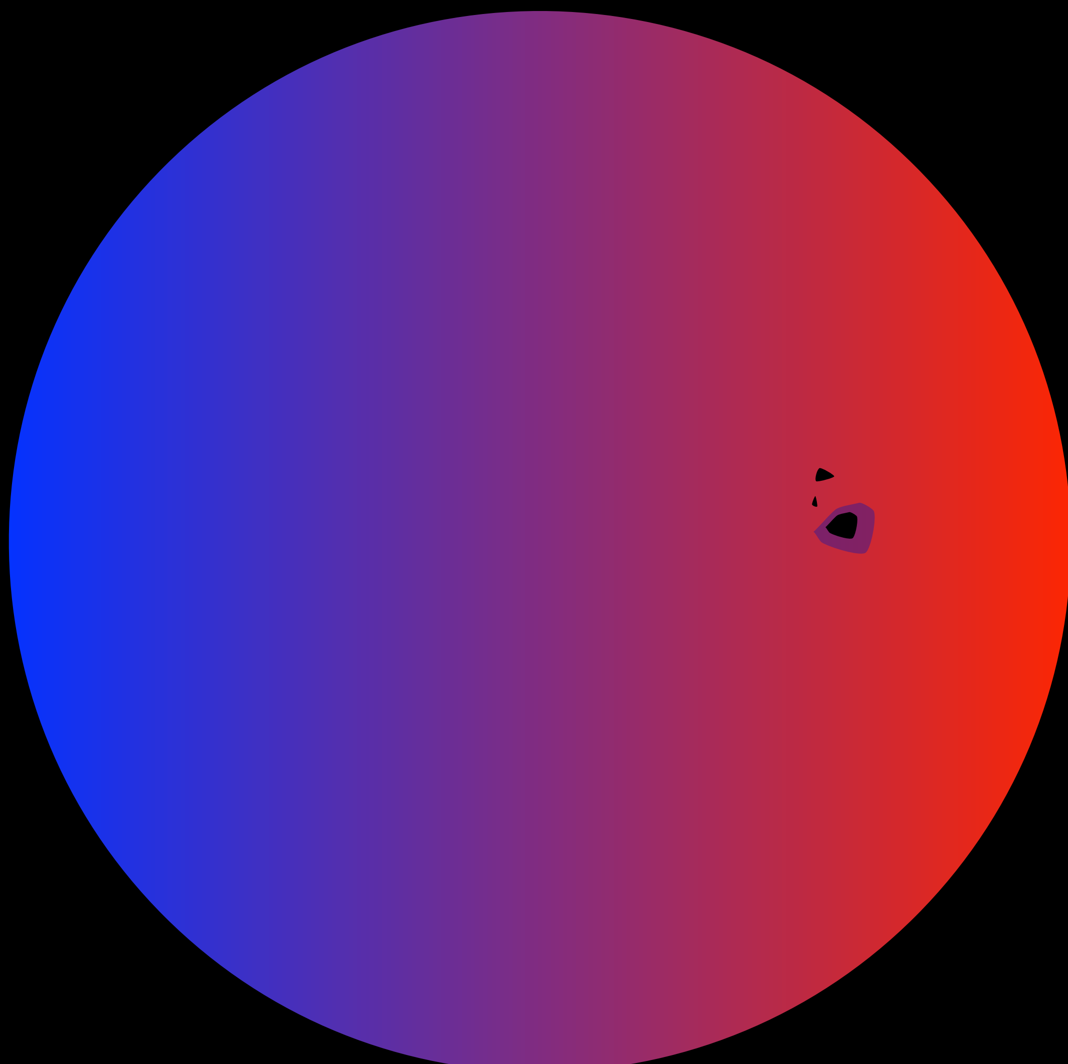
up (towards us)
down (away from us)

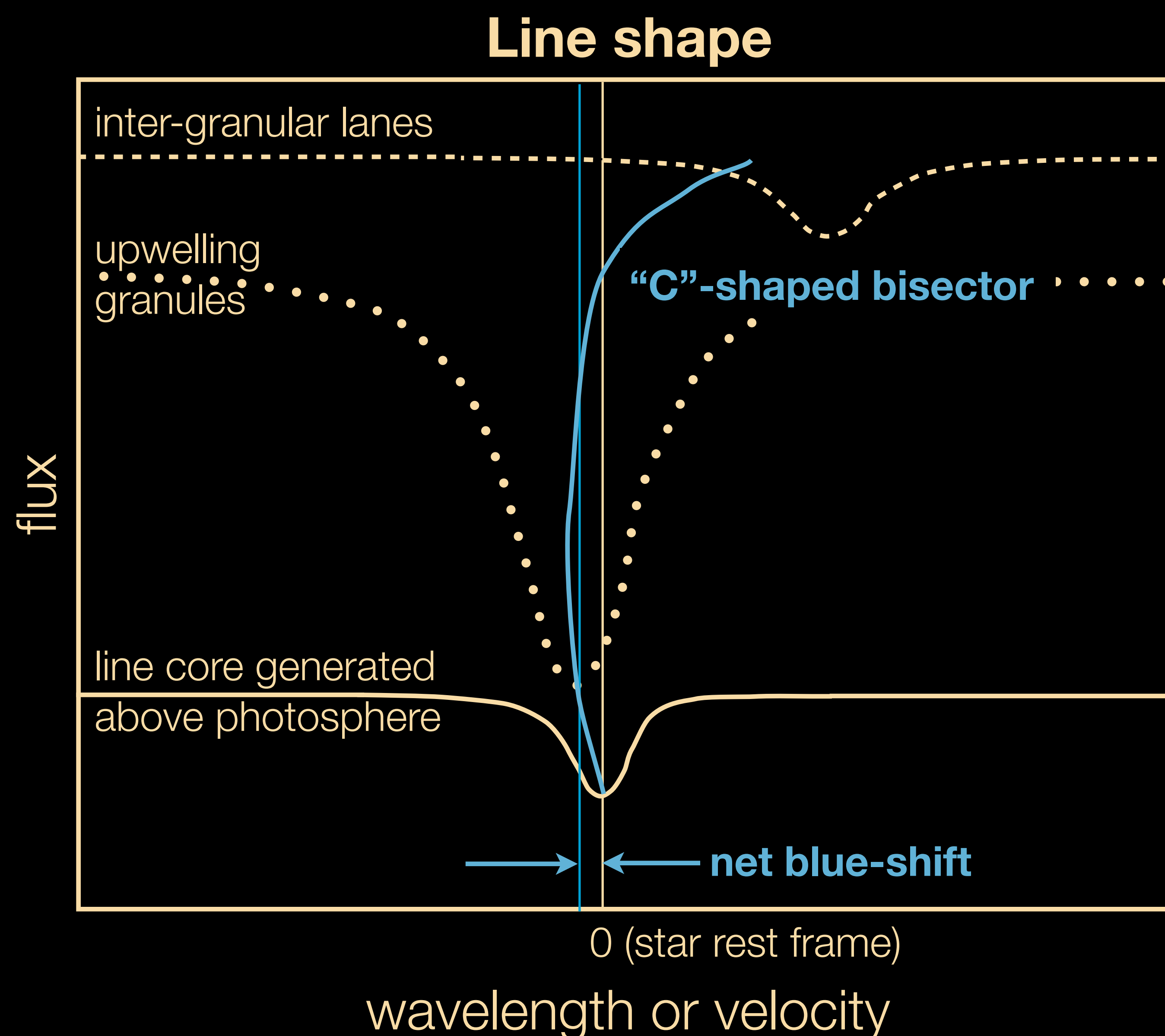
Line shape



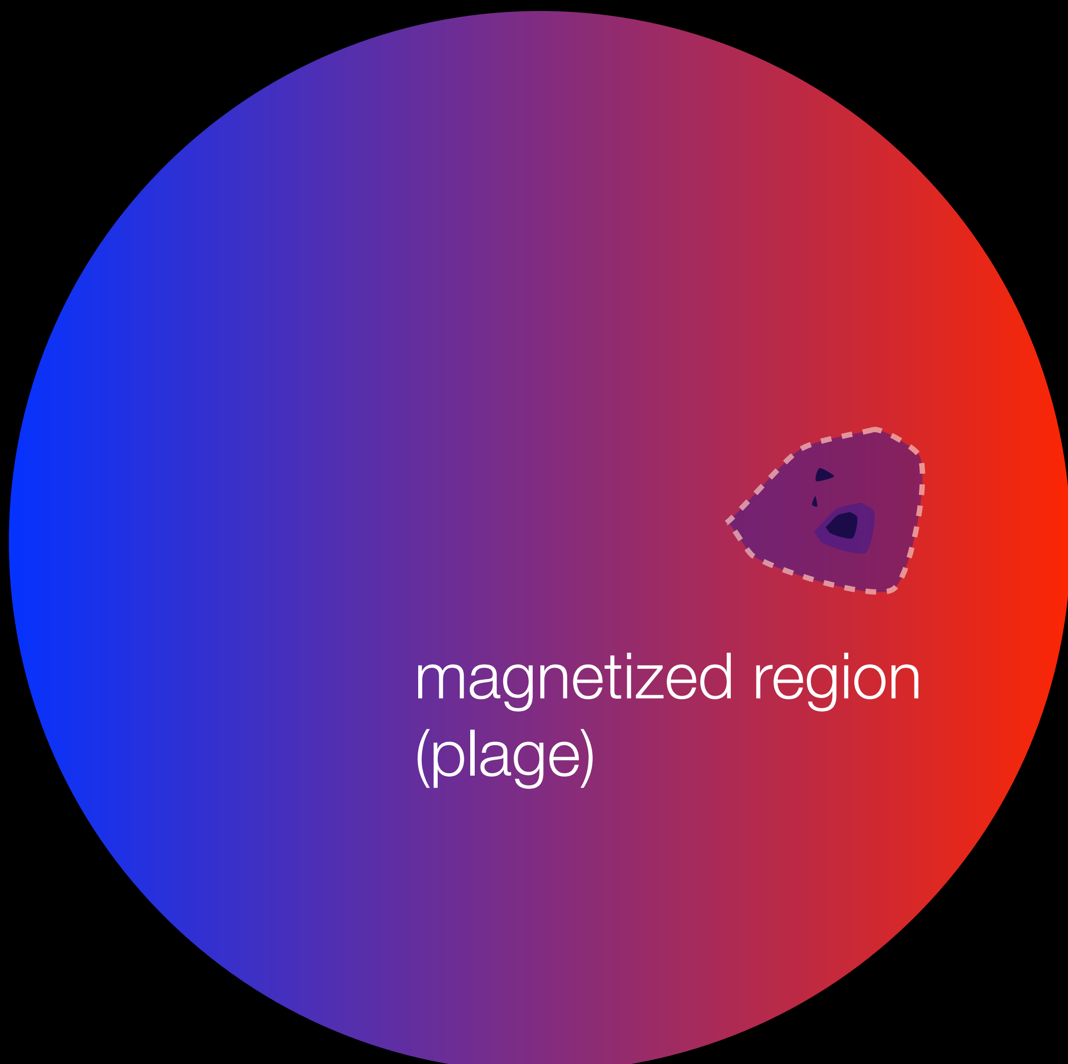
Line shape and absolute convective blue-shift depend on line strength (Gray 2009)

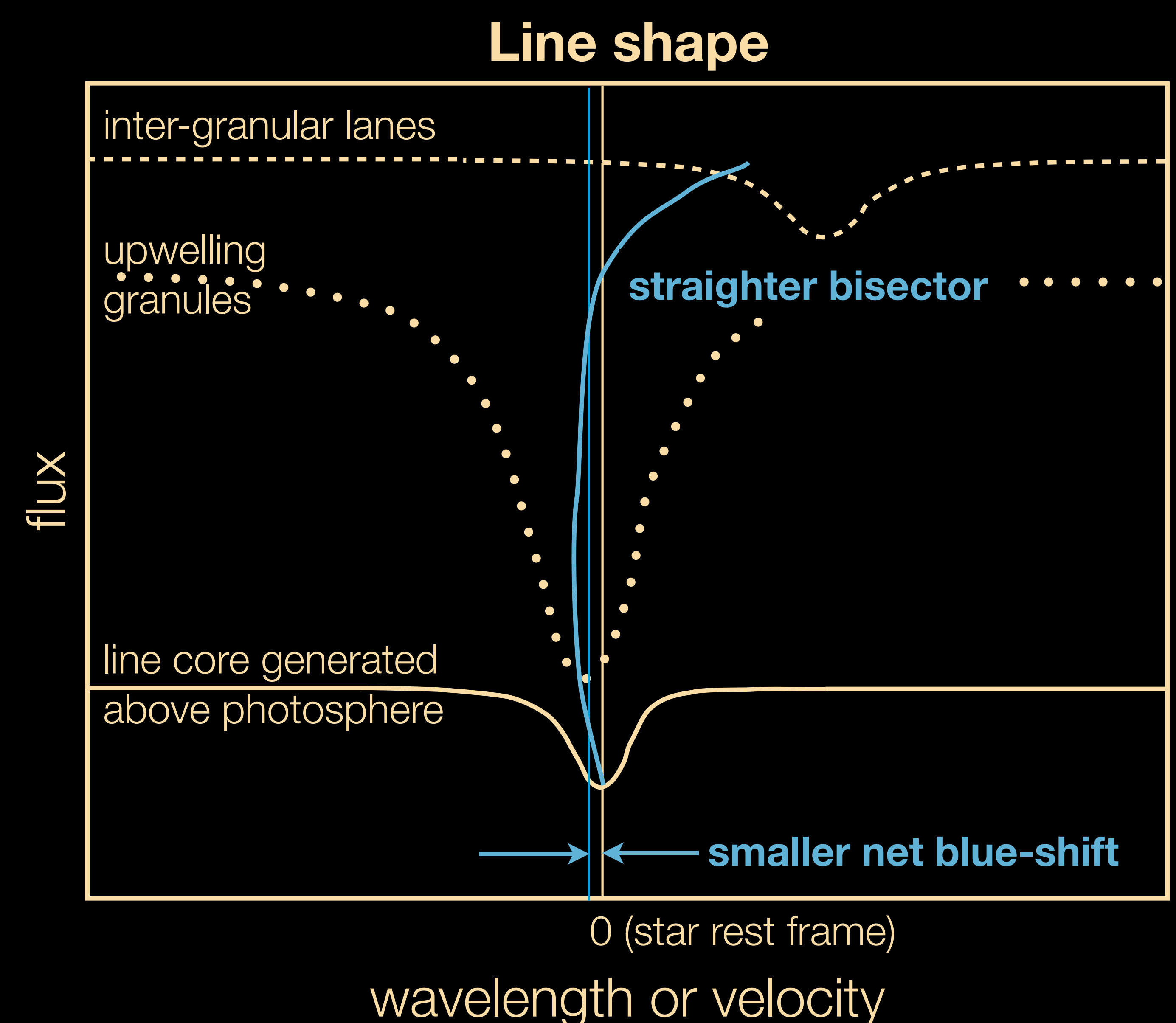
Spectral line asymmetries in “normal” photosphere



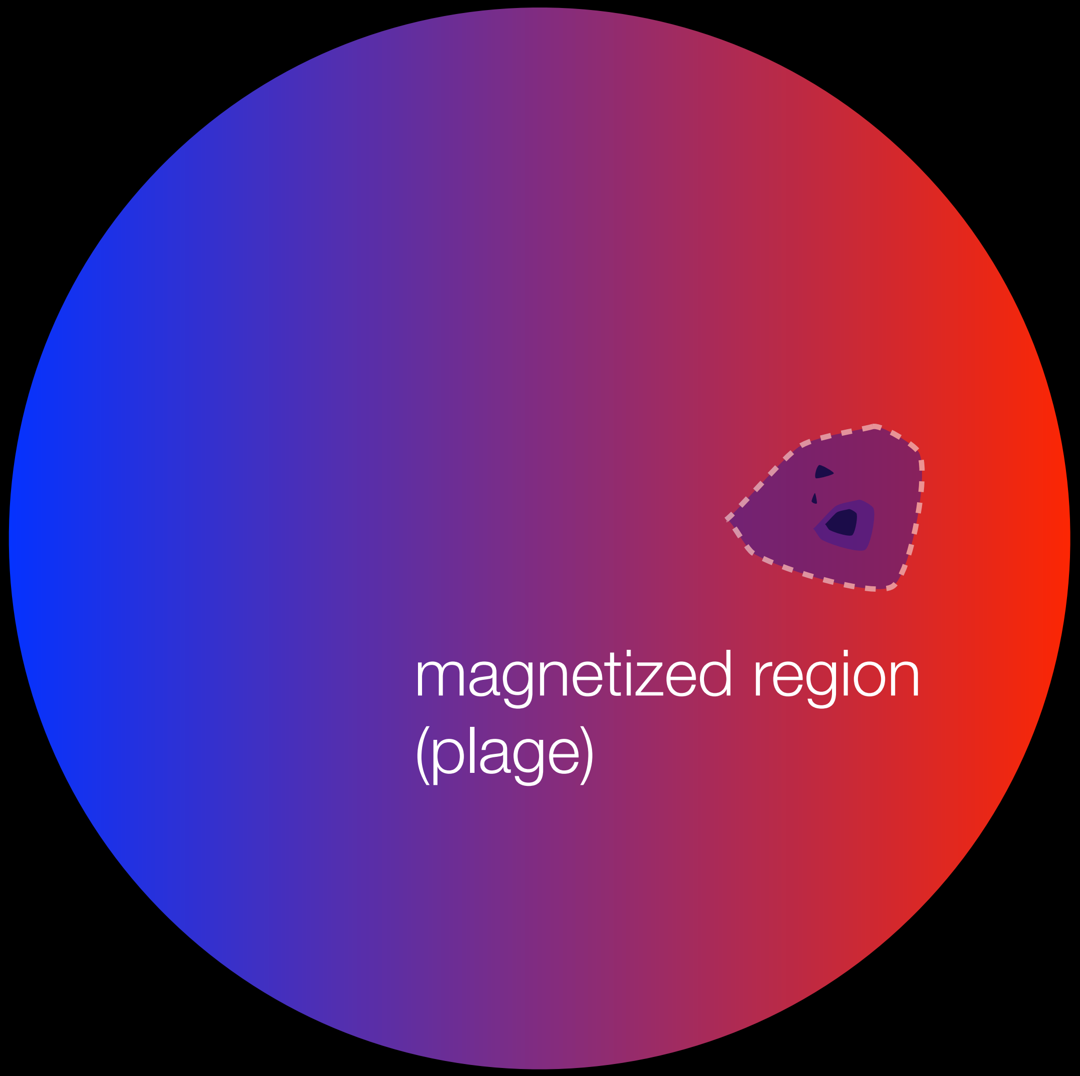


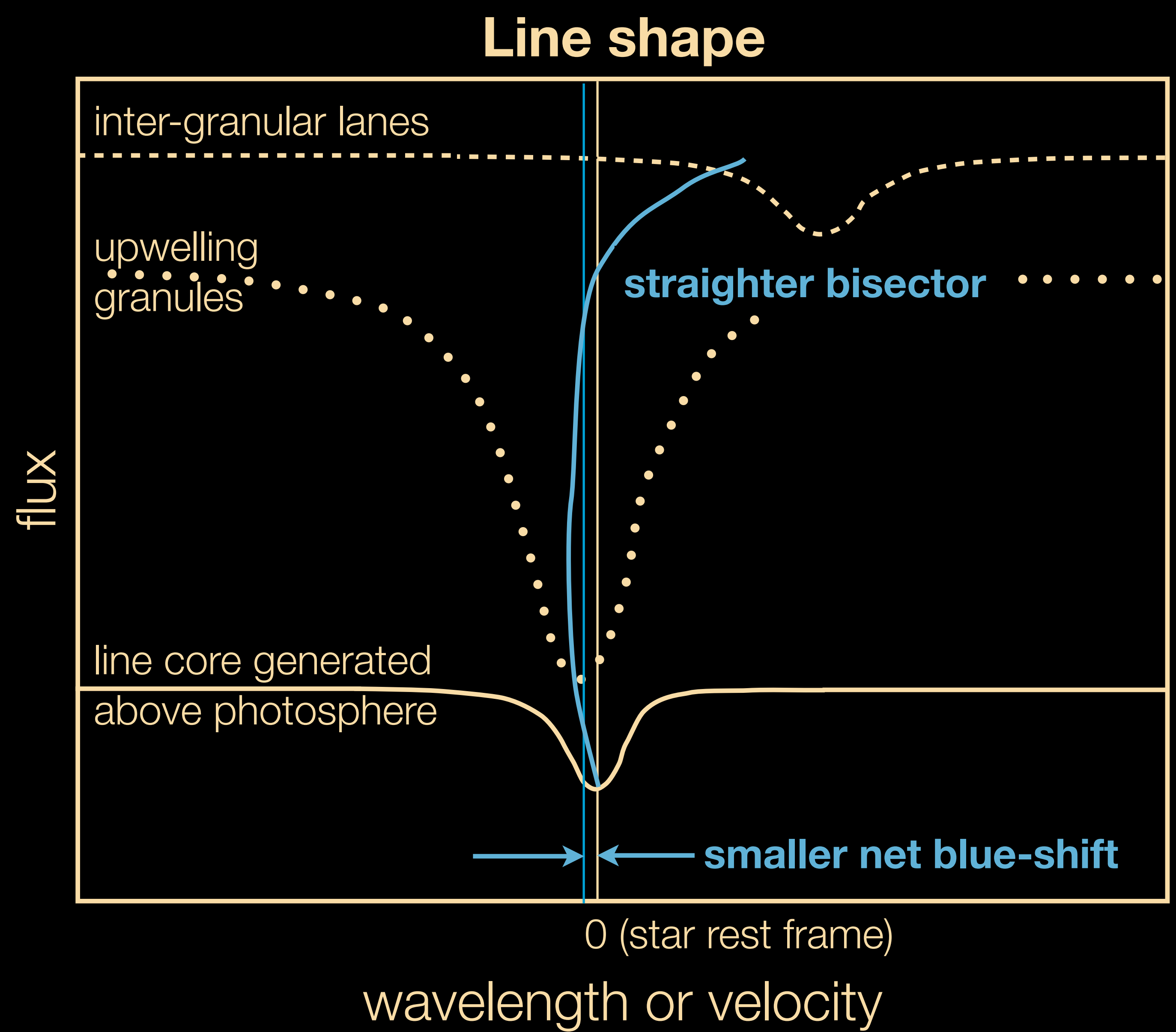
RV effects of activity - 2: convective blueshift suppression





RV effects of activity - 2:
convective blueshift suppression

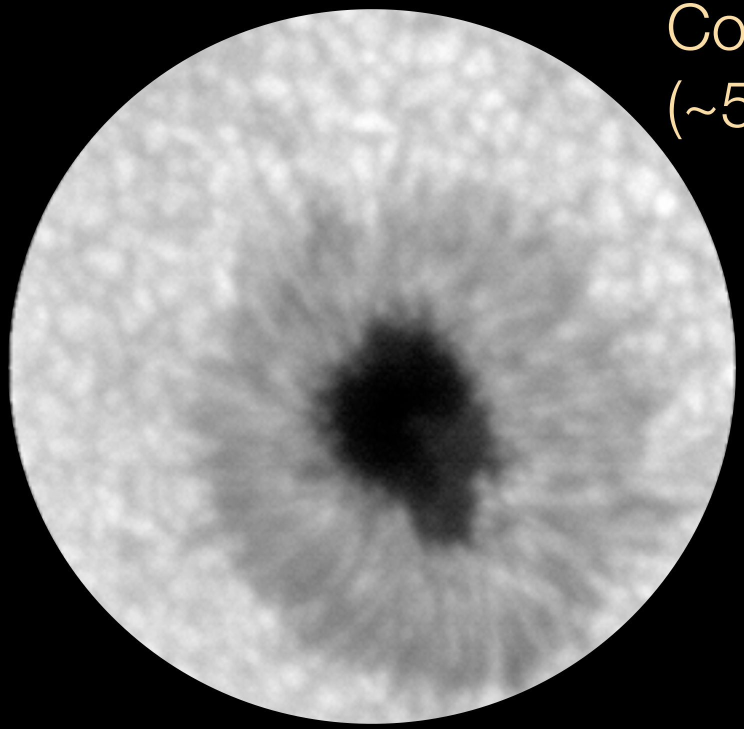




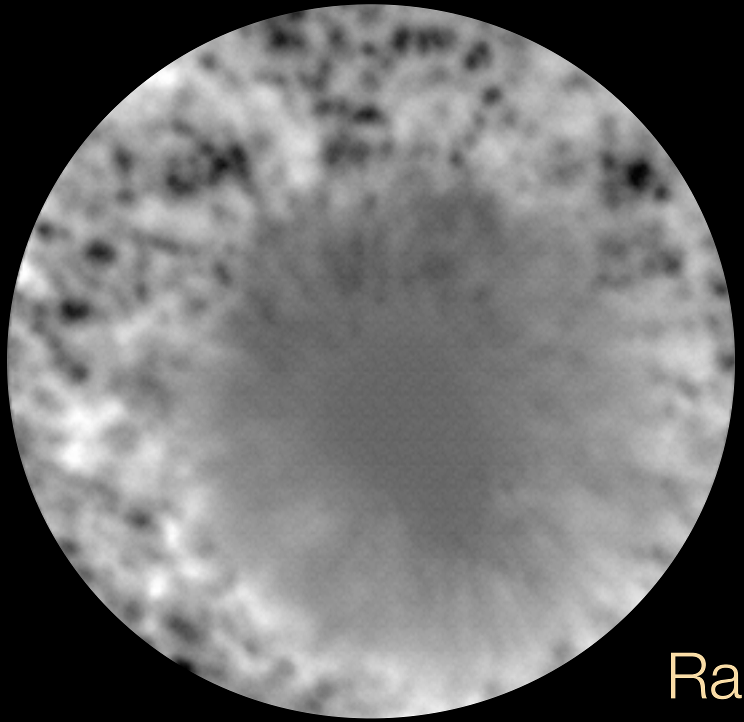
This dominates over the effect of spots for the Sun (Meunier et al. 2010)

Thermal and velocity structure of Sunspots

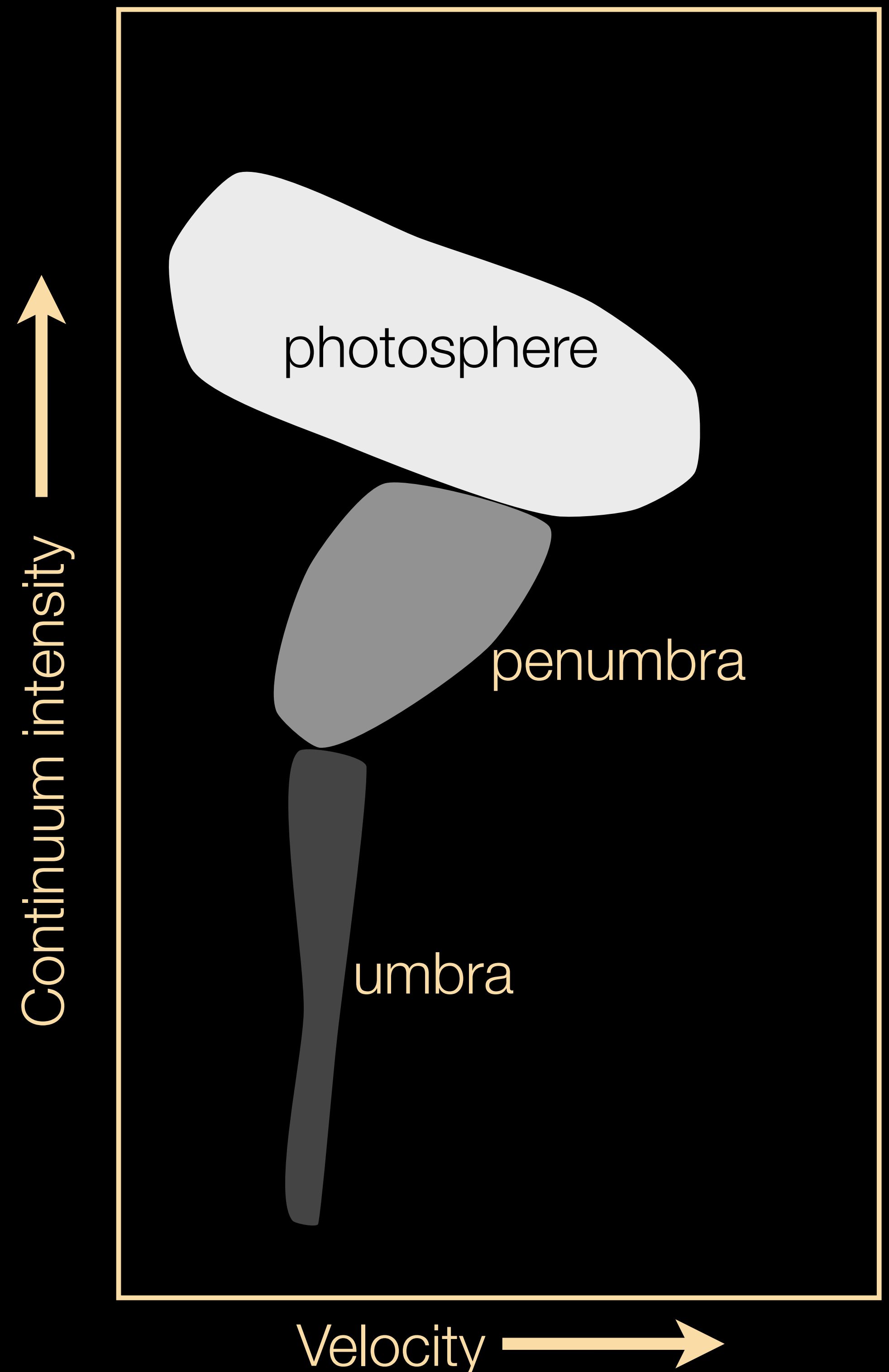
Balasubramaniam, ApJ, 2002



Continuum intensity
(~557 nm)



Radial velocity
(relative to umbra)



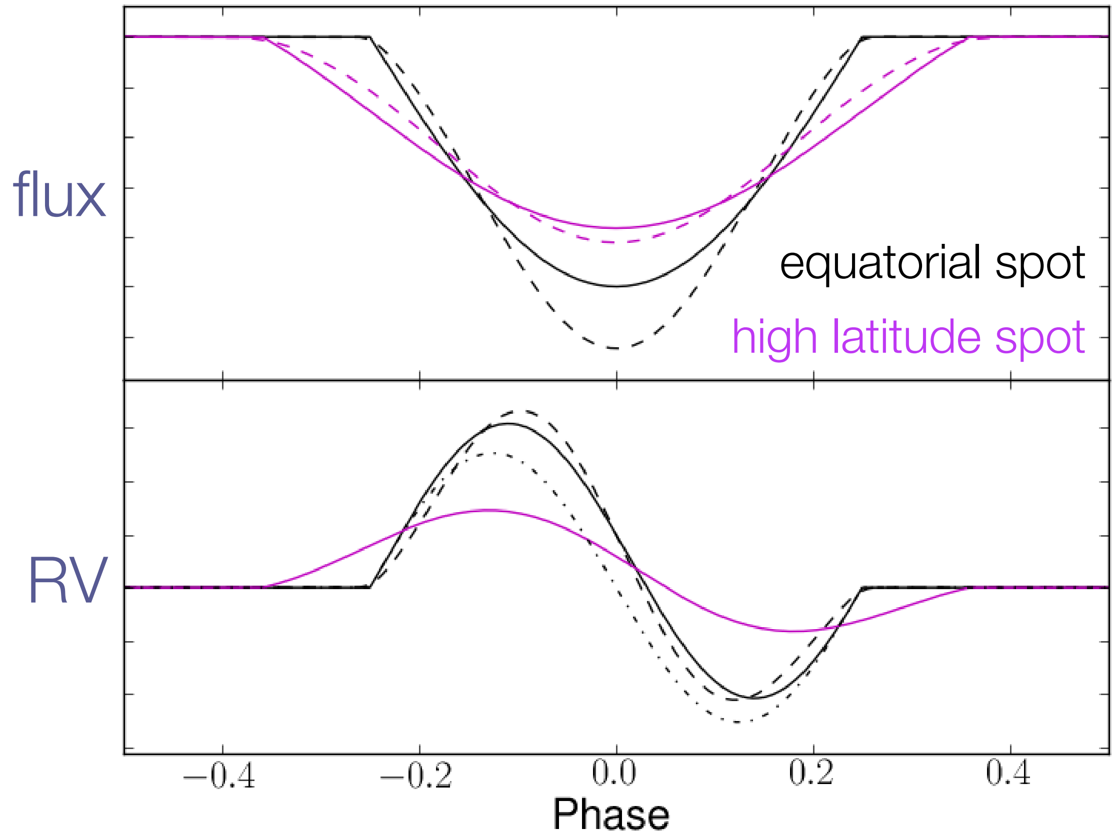
Calibrating activity effects in RV data

- Correlation with bisector span (Bonfils et al. 2007, Boisse et al. 2009).
- Correlation with Ca H & K index (Boisse et al. 2011, Dumusque et al. 2011, Meunier et al. 2013).
  - Long-term component of Ca index for “activity cycle” (Dumusque et al. 2012)
- Sine-fitting at harmonics of the rotation period (too many to list...)
- Light curves
  - Spot modelling (Lanza et al. 2007, 2010, Boisse et al. 2012)
  - *FF’ method* (Aigrain et al. 2012)

RV effects of activity - 1:

distortion of rotation profile

Perturbation to full disk measurement due to one spot



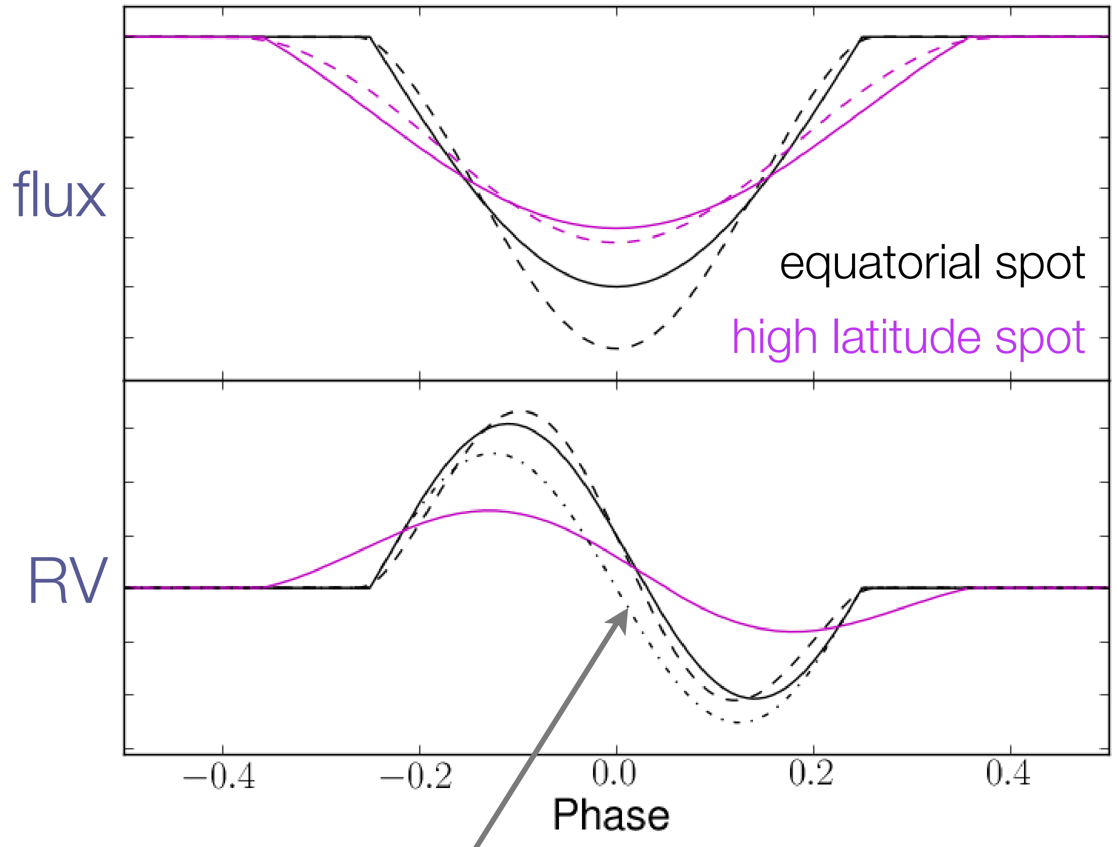
Can show that:

$\Delta V_{rot} \propto \Delta F \times d(\Delta F)/dt$

(Aigrain, Pont & Zucker 2012)

RV effects of activity - 2: convective blue-shift suppression

Perturbation to full disk measurement due to one spot



including convective blue-shift suppression

Can show that:

$\Delta V_{conv} \propto \Delta F^2$

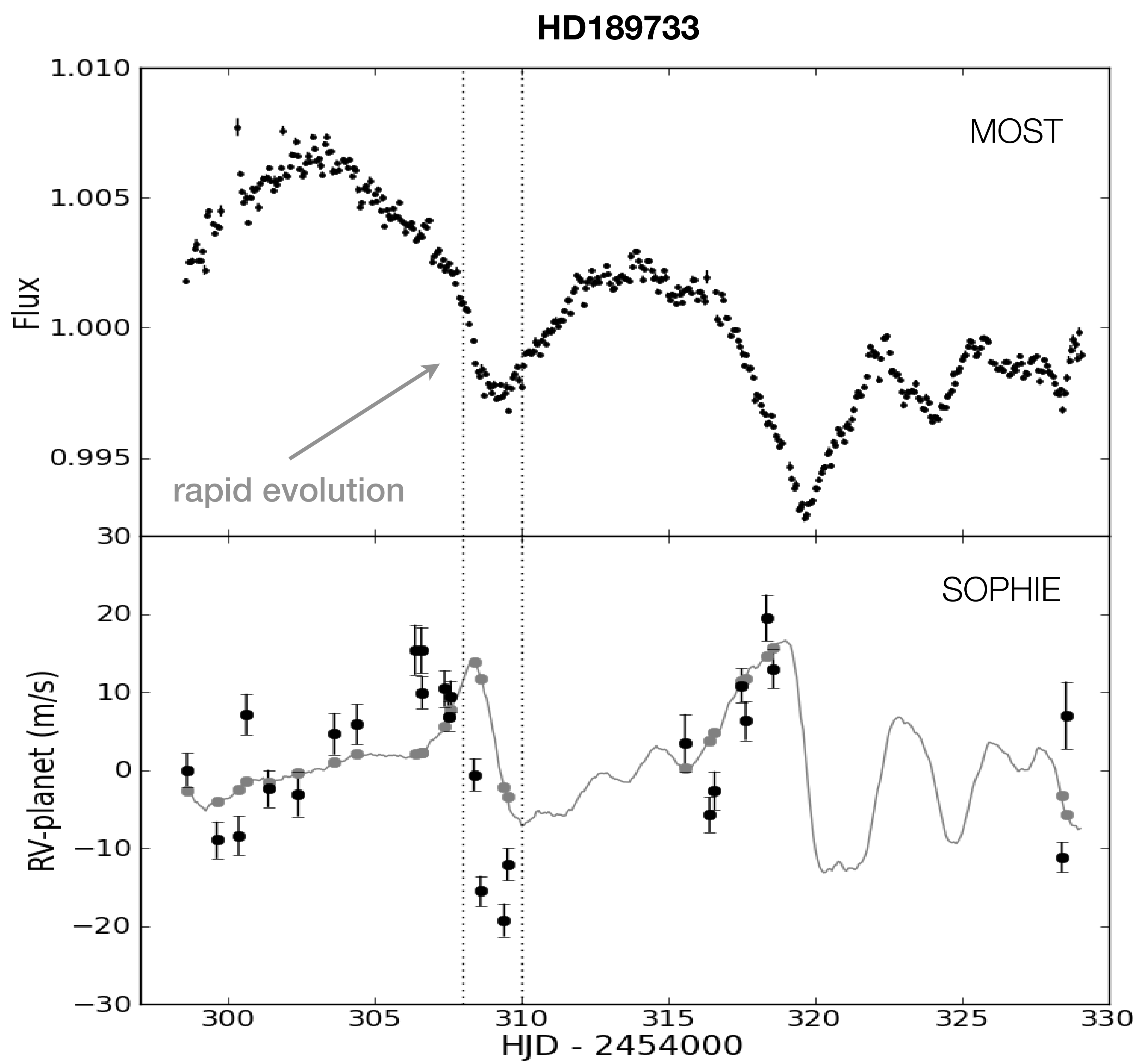
(Aigrain, Pont & Zucker 2012)

FF’: simple but effective

Data from Boisse et al. (2009)

Performance equivalent to more sophisticated (and highly degenerate) spot models (cf. Lanza et al. 2010)

Accurate to the level of SOPHIE systematics (5-10 m/s)

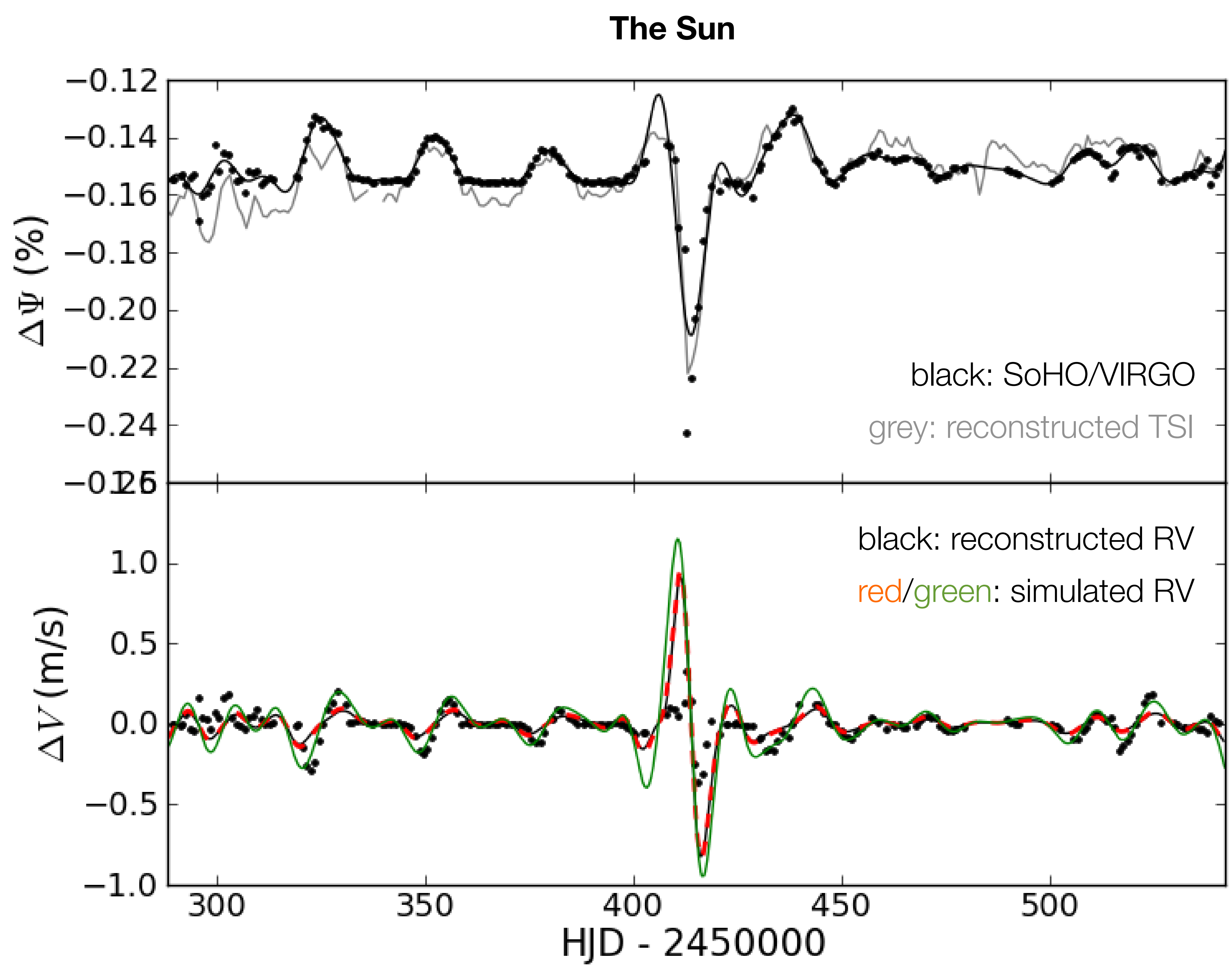


Example: the Sun

No full-disk, full spectrum, long-term RV measurements of the Sun available

Using reconstruction from Meunier et al. (2010b)

Simulated RVs match reconstruction to < 1 m/s



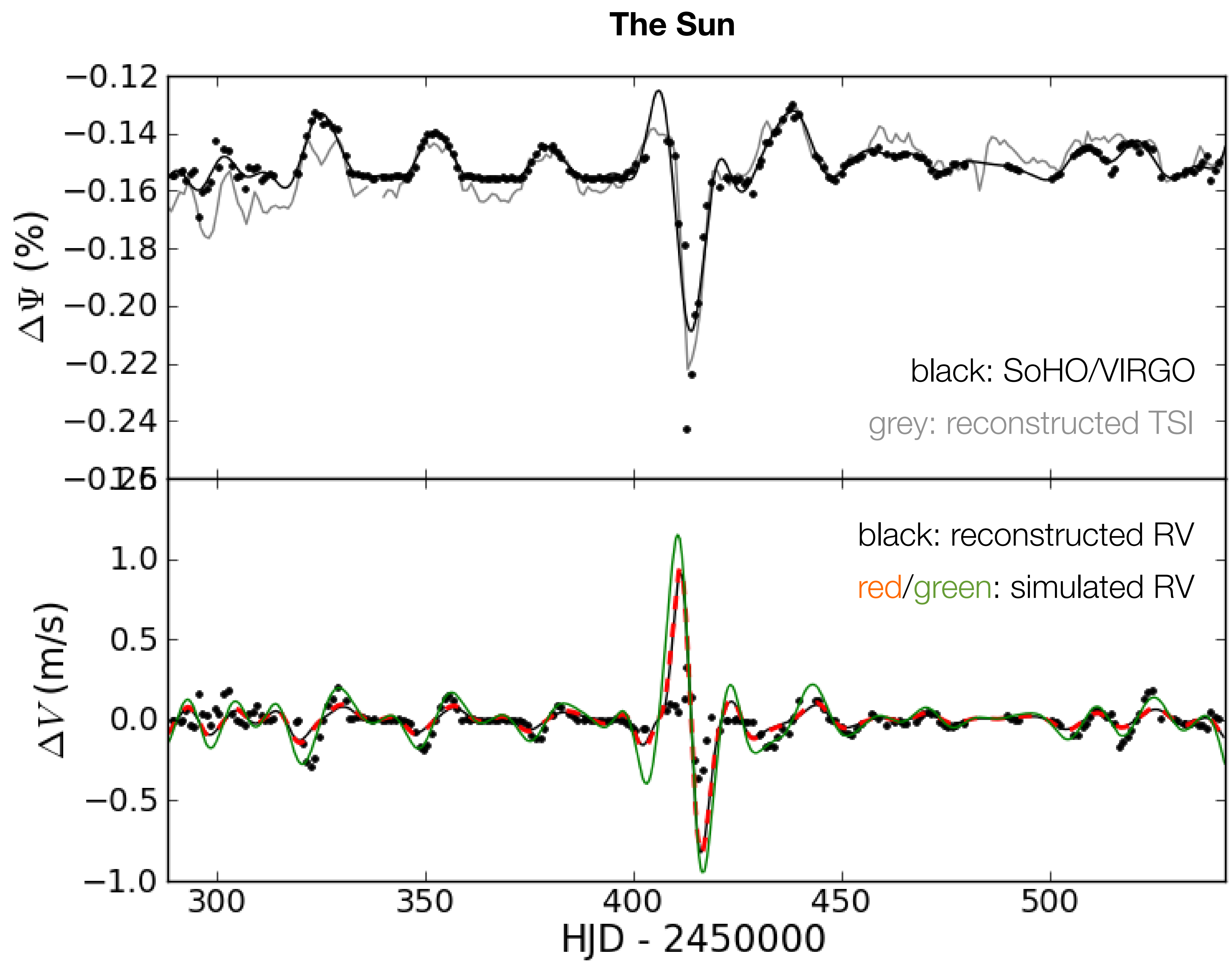
Example: the Sun

No full-disk, full spectrum, long-term RV measurements of the Sun available

Using reconstruction from Meunier et al. (2010b)

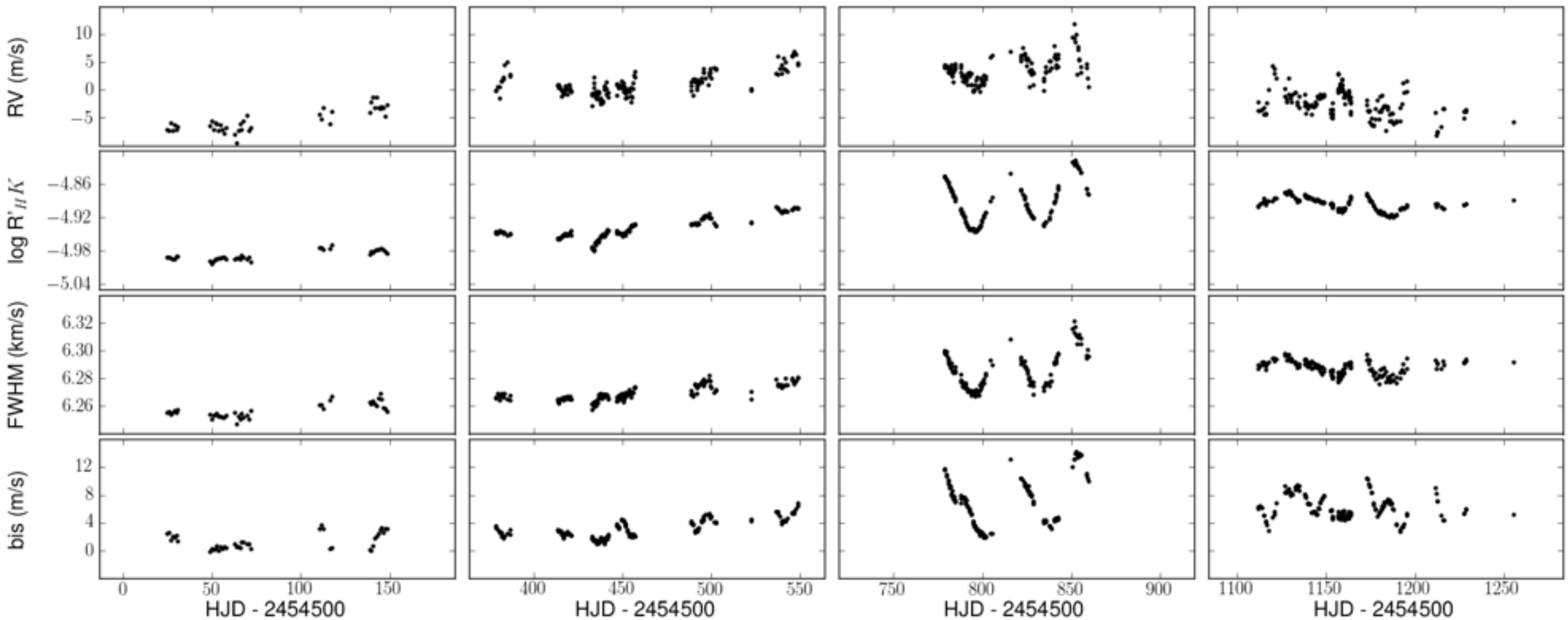
Simulated RVs match reconstruction to < 1 m/s

Recently demonstrated on HARPS-N observations of CoRoT-7 (Haywood et al., submitted)



What if we have only spectra?

αCen B (Dumusque et al. 2012). HARPS spectra provide:
RVs, chromospheric activity (log R'_{HK}), line width (FWHM) and asymmetry (bisector span)



Earth-mass planet in 3.2 day orbit inferred from 4 years of HARPS data
NB: RVs shown here after subtracting linear trend from binary orbit.

Modelling the activity signal in αCen B

Dumusque et al. model
for binary orbit + activity

23 free parameters
several arbitrary assumptions
strong degeneracies
error propagation partial

$$
\begin{aligned}
\text{subset 2008} \quad &: \quad lin0 + lin1 \cdot JDB_{2008} + lin2 \cdot JDB^2_{2008} + A_{RV-Rhk} \cdot RHK_{low\,freq,2008} \\
\text{subset 2009} \quad &: \quad lin0 + lin1 \cdot JDB_{2009} + lin2 \cdot JDB^2_{2009} + A_{RV-Rhk} \cdot RHK_{low\,freq,2009} \\
&\quad +A11s \cdot sin(\frac{2\pi}{P1}) \cdot JDB_{2009} + A11c \cdot cos(\frac{2\pi}{P1}) \cdot JDB_{2009} \\
&\quad +A12s \cdot sin(\frac{2\pi}{P1/2}) \cdot JDB_{2009} + A12c \cdot cos(\frac{2\pi}{P1/2}) \cdot JDB_{2009} \\
\text{subset 2010} \quad &: \quad lin0 + lin1 \cdot JDB_{2010} + lin2 \cdot JDB^2_{2010} + A_{RV-Rhk} \cdot RHK_{low\,freq,2010} \\
&\quad +A21s \cdot sin(\frac{2\pi}{P2}) \cdot JDB_{2010} + A21c \cdot cos(\frac{2\pi}{P2}) \cdot JDB_{2010} \\
&\quad +A23s \cdot sin(\frac{2\pi}{P2/3}) \cdot JDB_{2010} + A23c \cdot cos(\frac{2\pi}{P2/3}) \cdot JDB_{2010} \\
&\quad +A24s \cdot sin(\frac{2\pi}{P2/4}) \cdot JDB_{2010} + A24c \cdot cos(\frac{2\pi}{P2/4}) \cdot JDB_{2010} \\
\text{subset 2011} \quad &: \quad lin0 + lin1 \cdot JDB_{2011} + lin2 \cdot JDB^2_{2011} + A_{RV-Rhk} \cdot RHK_{low\,freq,2011} \\
&\quad +A31s \cdot sin(\frac{2\pi}{P3}) \cdot JDB_{2011} + A31c \cdot cos(\frac{2\pi}{P3}) \cdot JDB_{2011} \\
&\quad +A32s \cdot sin(\frac{2\pi}{P3/2}) \cdot JDB_{2011} + A32c \cdot cos(\frac{2\pi}{P3/2}) \cdot JDB_{2011} \\
&\quad +A33s \cdot sin(\frac{2\pi}{P3/3}) \cdot JDB_{2011} + A33c \cdot cos(\frac{2\pi}{P3/3}) \cdot JDB_{2011}
\end{aligned}
$$

Modelling the activity signal in αCen B

Dumusque et al. model
for binary orbit + activity

23 free parameters
several arbitrary assumptions
strong degeneracies
error propagation partial

$$
\begin{aligned}
\text{subset 2008} \quad : \quad & lin0 + lin1 \cdot JDB_{2008} + lin2 \cdot JDB_{2008}^2 + A_{RV-Rhk} \cdot RHK_{low\,freq,2008} \\
\text{subset 2009} \quad : \quad & lin0 + lin1 \cdot JDB_{2009} + lin2 \cdot JDB_{2009}^2 + A_{RV-Rhk} \cdot RHK_{low\,freq,2009} \\
& + A11s \cdot sin(\frac{2\pi}{P1}) \cdot JDB_{2009} + A11c \cdot cos(\frac{2\pi}{P1}) \cdot JDB_{2009} \\
& + A12s \cdot sin(\frac{2\pi}{P1/2}) \cdot JDB_{2009} + A12c \cdot cos(\frac{2\pi}{P1/2}) \cdot JDB_{2009} \\
\text{subset 2010} \quad : \quad & lin0 + lin1 \cdot JDB_{2010} + lin2 \cdot JDB_{2010}^2 + A_{RV-Rhk} \cdot RHK_{low\,freq,2010} \\
& + A21s \cdot sin(\frac{2\pi}{P2}) \cdot JDB_{2010} + A21c \cdot cos(\frac{2\pi}{P2}) \cdot JDB_{2010} \\
& + A23s \cdot sin(\frac{2\pi}{P2/3}) \cdot JDB_{2010} + A23c \cdot cos(\frac{2\pi}{P2/3}) \cdot JDB_{2010} \\
& + A24s \cdot sin(\frac{2\pi}{P2/4}) \cdot JDB_{2010} + A24c \cdot cos(\frac{2\pi}{P2/4}) \cdot JDB_{2010} \\
\text{subset 2011} \quad : \quad & lin0 + lin1 \cdot JDB_{2011} + lin2 \cdot JDB_{2011}^2 + A_{RV-Rhk} \cdot RHK_{low\,freq,2011} \\
& + A31s \cdot sin(\frac{2\pi}{P3}) \cdot JDB_{2011} + A31c \cdot cos(\frac{2\pi}{P3}) \cdot JDB_{2011} \\
& + A32s \cdot sin(\frac{2\pi}{P3/2}) \cdot JDB_{2011} + A32c \cdot cos(\frac{2\pi}{P3/2}) \cdot JDB_{2011} \\
& + A33s \cdot sin(\frac{2\pi}{P3/3}) \cdot JDB_{2011} + A33c \cdot cos(\frac{2\pi}{P3/3}) \cdot JDB_{2011}
\end{aligned}
$$

Can one do better?
Activity is stochastic -> model it as a Gaussian process

An aside: Gaussian processes

An aside: Gaussian processes

- Formally, a Gaussian process (GP) is a collection of data points, any subset of which has a multivariate normal distribution: $\boldsymbol{y} \sim \mathcal{N}\{\boldsymbol{m};\mathrm{K}\}$

An aside: Gaussian processes

- Formally, a Gaussian process (GP) is a collection of data points, any subset of which has a multivariate normal distribution: $\boldsymbol{y} \sim \mathcal{N}\{\boldsymbol{m};\mathrm{K}\}$
- The mean vector $\boldsymbol{m}$ encodes the deterministic component of the model e.g. $\boldsymbol{m} = f(\boldsymbol{t},\boldsymbol{\theta})$

An aside: Gaussian processes

- Formally, a Gaussian process (GP) is a collection of data points, any subset of which has a multivariate normal distribution: $\boldsymbol{y} \sim \mathcal{N}\{\boldsymbol{m};\mathrm{K}\}$
- The mean vector $\boldsymbol{m}$ encodes the deterministic component of the model e.g. $\boldsymbol{m} = f(\boldsymbol{t},\boldsymbol{\theta})$
- The covariance matrix K encodes the stochastic component
  - standard white Gaussian noise: $\mathrm{K} = \sigma^2\mathbb{I}$

An aside: Gaussian processes

- Formally, a Gaussian process (GP) is a collection of data points, any subset of which has a multivariate normal distribution: $\boldsymbol{y} \sim \mathcal{N}\{\boldsymbol{m};\mathrm{K}\}$
- The mean vector $\boldsymbol{m}$ encodes the deterministic component of the model e.g. $\boldsymbol{m} = f(\boldsymbol{t},\boldsymbol{\theta})$
- The covariance matrix K encodes the stochastic component
    - standard white Gaussian noise: $\mathrm{K} = \sigma^2\mathbb{I}$
- Generalise to non-diagonal covariance (a.k.a correlated noise): $\mathrm{K}_{ij} = k(t_i,t_j,\boldsymbol{\Phi})$,
    - e.g. $k(t_i,t_j,\boldsymbol{\Phi}) = A^2 \exp[-(t_i-t_j)^2 / 2\ell^2]$

An aside: Gaussian processes

- Formally, a Gaussian process (GP) is a collection of data points, any subset of which has a multivariate normal distribution: $\boldsymbol{y} \sim \mathcal{N}\{\boldsymbol{m};\mathrm{K}\}$
- The mean vector $\boldsymbol{m}$ encodes the deterministic component of the model e.g. $\boldsymbol{m} = f(\boldsymbol{t},\boldsymbol{\theta})$
- The covariance matrix K encodes the stochastic component
    - standard white Gaussian noise: $\mathrm{K} = \sigma^2\mathbb{I}$
- Generalise to non-diagonal covariance (a.k.a correlated noise): $\mathrm{K}_{ij} = k(t_i,t_j,\boldsymbol{\Phi})$,
    - e.g. $k(t_i,t_j,\boldsymbol{\Phi}) = A^2 \exp[-(t_i-t_j)^2 / 2\ell^2]$
- This sets up a probability distribution over *functions* with specific properties
    - here: smooth, amplitude A, timescale ℓ)

An aside: Gaussian processes

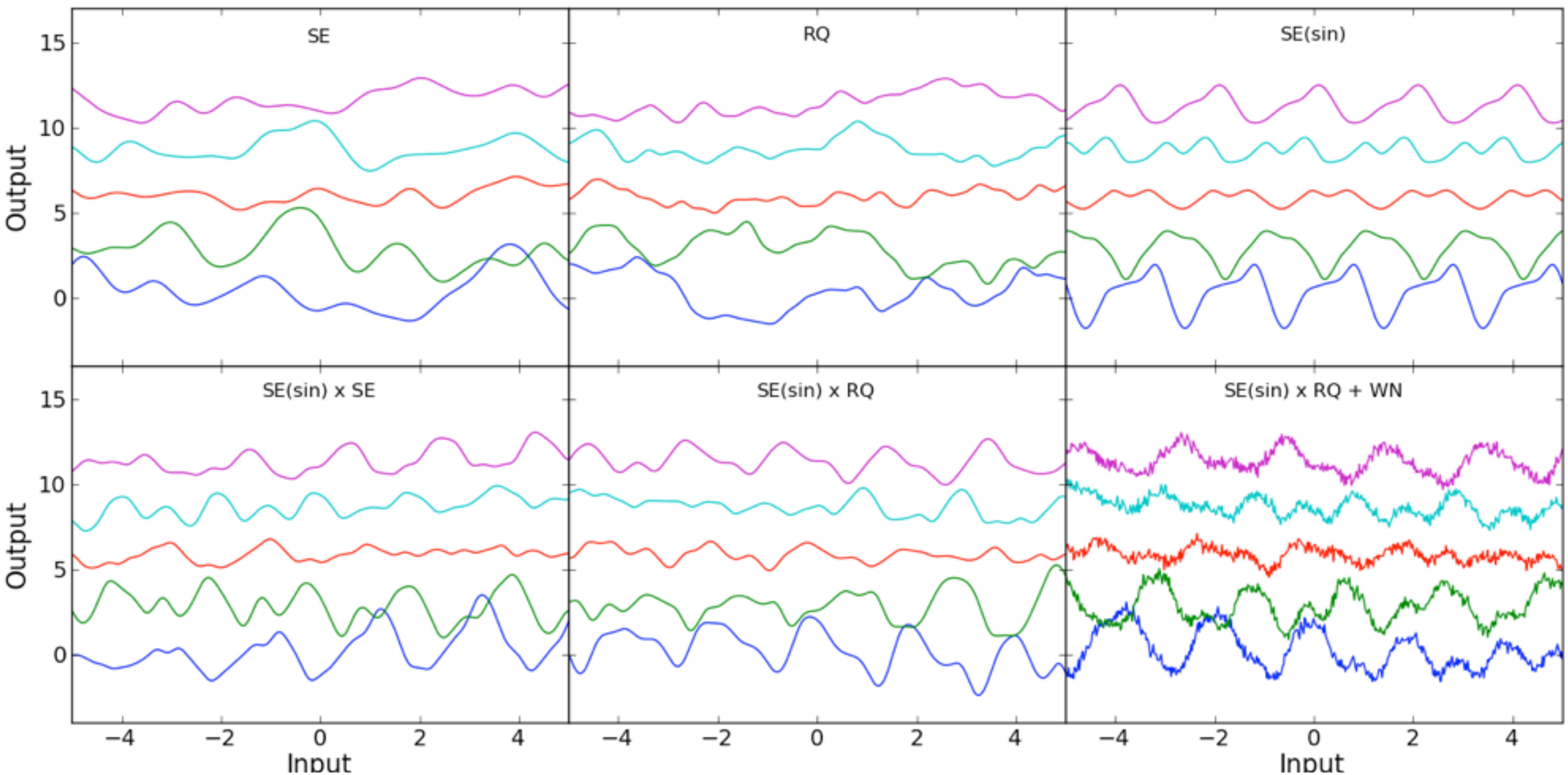
- Formally, a Gaussian process (GP) is a collection of data points, any subset of which has a multivariate normal distribution: $\boldsymbol{y} \sim \mathcal{N}\{\boldsymbol{m};\mathrm{K}\}$
- The mean vector $\boldsymbol{m}$ encodes the deterministic component of the model e.g. $\boldsymbol{m} = f(\boldsymbol{t},\boldsymbol{\theta})$
- The covariance matrix K encodes the stochastic component
    - standard white Gaussian noise: $\mathrm{K} = \sigma^2 \mathbb{I}$
- Generalise to non-diagonal covariance (a.k.a correlated noise): $\mathrm{K}_{ij} = k(t_i,t_j,\boldsymbol{\Phi})$,
    - e.g. $k(t_i,t_j,\boldsymbol{\Phi}) = A^2 \exp[-(t_i-t_j)^2 / 2\ell^2]$
- This sets up a probability distribution over *functions* with specific properties
    - here: smooth, amplitude A, timescale ℓ)
- With GPs it's easy to
    - model multiple time-series simultaneously, incl. derivative / integral observations
    - perform Bayesian inference on $\boldsymbol{\theta},\boldsymbol{\Phi}$ e.g. using MCMC
    - propagate uncertainties rigorously

GPs for stellar activity

aperiodic, single timescale

aperiodic, multiple timescales

periodic (unknown shape)



quasi-periodic,
single evolution timescale

quasi-periodic,
multiple evolution timescales

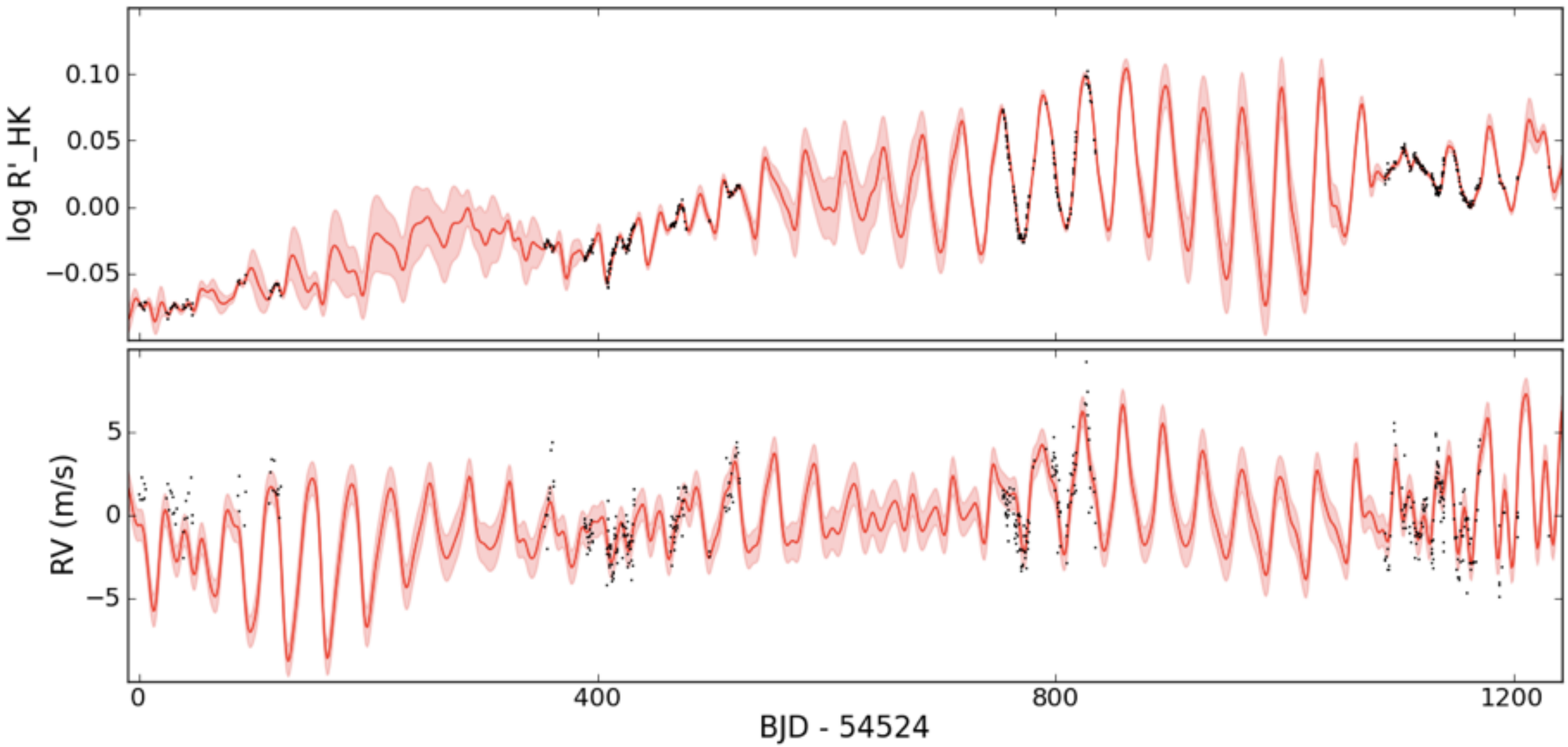
quasi-periodic
plus white noise

Modelling the activity signal in αCen B

Model both $\log R'_{HK}$ and RV as linear combinations of underlying process F^2 and its time derivative FF'

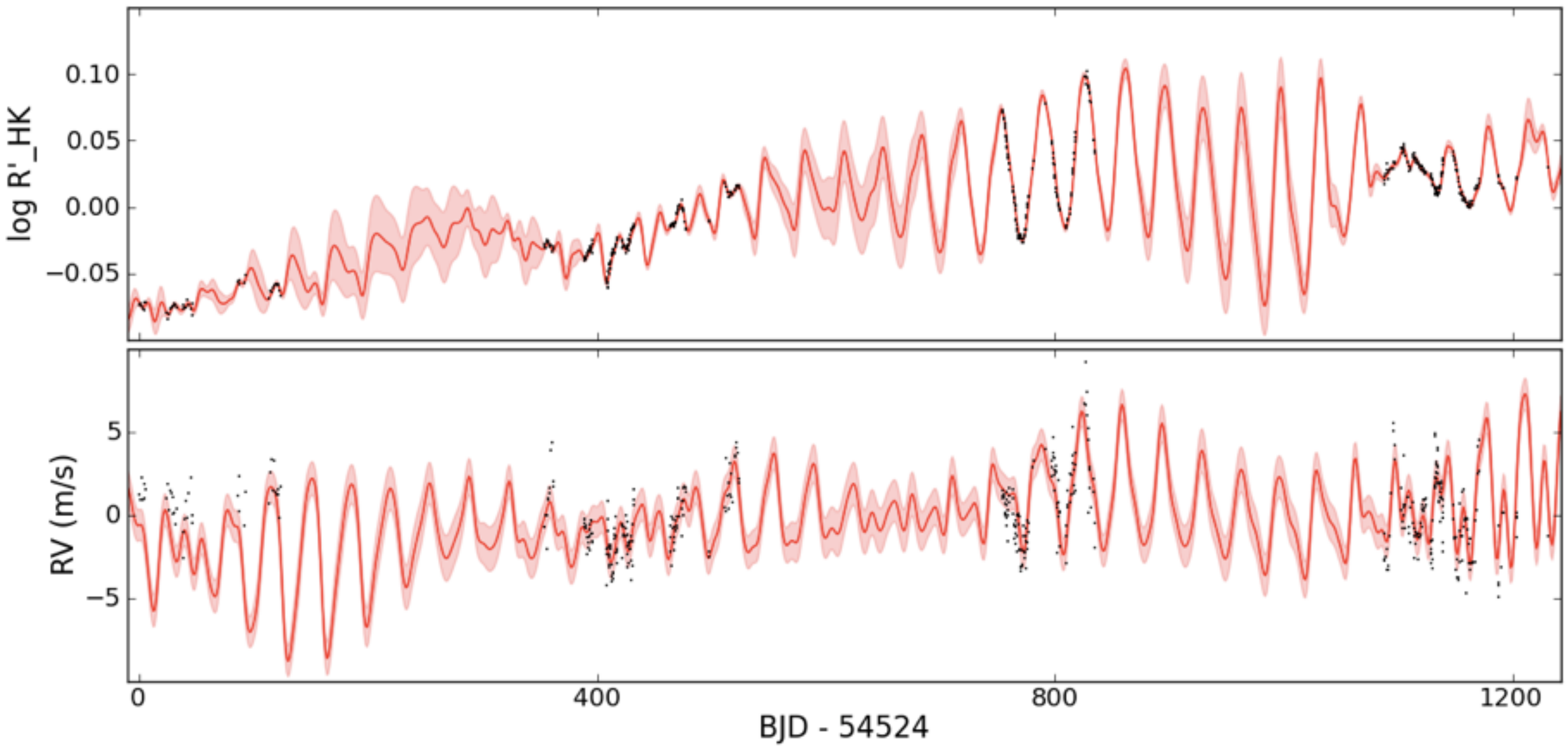
Modelling the activity signal in αCen B

Model both log R'_{HK} and RV as linear combinations of underlying process F^2 and its time derivative FF'



Modelling the activity signal in αCen B

Model both log R'_{HK} and RV as linear combinations of underlying process F^2 and its time derivative FF'



Can the RV variations be explained by activity only (no planet)?
Work in progress!!! Rajpaul et al. (in prep.)

To overcome activity effects in RV, we need…

To overcome activity effects in RV, we need…

- **many 100's of *high SNR* measurements for a few dozen stars**
  - **THE experiment proposed for 2.5m INT**

To overcome activity effects in RV, we need…

- **many 100‘s of *high SNR* measurements for a few dozen stars**
  - **THE experiment proposed for 2.5m INT**
- **detailed spectra modelling**
  - understand how spots / plage at different limb-angles affect different spectral lines

To overcome activity effects in RV, we need…

- **many 100‘s of *high SNR* measurements for a few dozen stars**
    - **THE experiment proposed for 2.5m INT**
- **detailed spectra modelling**
    - understand how spots / plage at different limb-angles affect different spectral lines
- continue to develop and test **“simple” correction approaches**
    - semi-parametric time-series modelling
    - different line-shape diagnostics
    - templates optimized to pick out activity effects
    - etc...

To overcome activity effects in RV, we need…

- **many 100's of *high SNR* measurements for a few dozen stars**
  - **THE experiment proposed for 2.5m INT**
- **detailed spectra modelling**
  - understand how spots / plage at different limb-angles affect different spectral lines
- continue to develop and test **"simple" correction approaches**
  - semi-parametric time-series modelling
  - different line-shape diagnostics
  - templates optimized to pick out activity effects
  - etc...
- precision RV machines **in the IR**

To overcome activity effects in RV, we need…

- **many 100's of *high SNR* measurements for a few dozen stars**
  - **THE experiment proposed for 2.5m INT**
- **detailed spectra modelling**
  - understand how spots / plage at different limb-angles affect different spectral lines
- continue to develop and test **"simple" correction approaches**
  - semi-parametric time-series modelling
  - different line-shape diagnostics
  - templates optimized to pick out activity effects
  - etc...
- precision RV machines **in the IR**
- let's not forget about **astrometry**: less sensitive to activity

- K2 = re-purposed Kepler mission
- Observations started March 2014, 2 years funded
- 4 x 85-day run per year, close to Ecliptic plane
- ~3000 M-dwarfs and ~3000 bright FGK dwarfs per run
- Important opportunity: **young open clusters** (ρOph, Pleiades, Hyades, M35, …)
- All data public immediately
- 1st data release end August